River weirs

Design, maintenance modification and removal

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Summary

A weir is an impounding structure in a watercourse over which water may flow and which increases water surface levels upstream over a range of flows. Weirs have been in use in the UK for hundreds of years, to manage water levels for mills, navigation, land drainage or flood risk management, provide a unique stage-discharge relationship for flow measurement, stabilise channels, enhance the landscape or provide recreation, or for commercial reasons such as abstraction, hydropower or fish counting. Fishing weirs have been used since Neolithic times.

A weir may perform useful functions, however there is increasing awareness of the impacts of weirs. A weir may obstruct the upstream migration of fish and prevent the downstream movement of sediment, with impacts on habitat and wildlife upstream and downstream. Sediment starvation may increase the risk of scour downstream. Weirs may also present a safety hazard and people drown at weirs every weir in the UK.

This good practice guide replaces guidance by Rickard *et al* (2003). Although comprehensive, lessons have been learned in terms of operational safety since publication, and the implementation of the Water Framework Directive (WFD) 2000 has led to a greater focus on weir removal. Although the majority of work on weirs is still carried out to maintain the current function(/s) of weirs, this guide leans heavily towards the alteration of weirs to benefit ecology, reflecting an industry need for greater guidance on topics such as geomorphology, environmental issues, alternatives to weirs and weir removal. Throughout the guide, the reader is be encouraged to ask whether a weir is the best option and to consider weir removal as a preferable design option, should assessments show this to be feasible.

This guide covers river weirs, including weirs on canalised rivers, canal weirs and river barrages, but does not cover dams, reservoir spillways, estuarine barrages or structures regulating natural lakes.

The target audience is broad and includes all those involved in the planning, design, construction, maintenance, modification or removal of river and canal weirs. The guide provides advice for regulatory authorities and professionals such as engineers, geomorphologists and architects, as well as navigation authorities, heritage bodies, weir preservation societies, abstraction licence holders, hydropower promoters, land, weir or mill owners, land agents and farmers. It is also useful for river and canal users or stakeholders, including fisheries owners, angling clubs and recreation bodies such as canoe or rowing clubs.

This guide aims to lead the reader through the process of managing weirs and is presented in three parts:

- **Part 1 (Chapters 1 and 2)** gives an overview of the functions of weirs, their impacts and the guidance framework surrounding their management.
- **Part 2 (Chapters 3 to 7)** provides guidance on the asset management process: setting objectives, assessing whether there is a need to intervene, the options available, how to compare options, and design, implementation and monitoring.
- **Part 3 (Chapters 8 to 15)** gives detailed guidance on asset management, law and policy, operational safety, the natural and historic environment, geomorphology, hydrology and hydraulics, foundations and structural design, and finally construction. Each chapter generally discusses the principles and issues before presenting or signposting detailed guidance on methods.
- **References** are given at the end of each chapter.
- **Examples and case studies** are provides throughout, with a guide to types of weir in **Appendix A1**, a design checklist in **Appendix A2** and detailed case studies in **Appendix A3**.

The sections that are likely to be of greatest relevance will depend on whether the reader is considering the removal of a weir, the refurbishment, repair or improvement of an existing weir, or the construction of a new or replacement weir.

The level of detail varies between topics according to the maturity of existing guidance. Where recognised, authoritative and accessible guidance already exists, the guide signposts this rather than reproduce existing material. Where guidance exists but is disparate, this guide brings the information together into a single non-contradictory source. Where science or evidence is emergent and/or controversial, the guide provides general pointers on emergent good practice, but does not seek to create new knowledge or reconcile all controversies.

There is some degree of repetition, particularly where issues are relevant to more than one topic, as it is anticipated that few readers will read this guide from cover-to-cover. The guide aims to direct readers towards the information that they are looking for, and also to alert them to other issues of which they may not be aware.

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Glossary

Abstraction	Removal of water from a source of supply (surface or groundwater), either temporarily or permanently.
Abstraction point	The point on a river from which water is abstracted.
Abutment	Wall that flanks the edge of a weir or hydraulic structure and supports the river-banks on each side of the weir.
Afflux	The maximum increase in water level in a river due to a weir relative to one that would exist without the weir.
Air draught	The height between the water surface and the highest point on a boat.
Air-regulated siphon	A spillway capable of acting as a partially pressurised pipe and maintaining near-constant upstream water level for variable discharge.
Anoxic	Oxygen-depleted.
Apron	A layer of scour-resistant material placed on the channel bed near to a weir or at the toe of river-bank protection.
Asset management	The co-ordinated activities of an organisation to realise value from its assets (ISO 55000:2014).
Attraction flow	Water discharge from or adjacent to the downstream outlet of a fish pass, which is intended to attract fish to the pass.
Backwater effect	A change in water depth in an open channel some distance upstream of a hydraulic structure or other flow obstruction. The extent of the backwater effect is known as the backwater length.
Baffles	Deflectors installed on the bottom or sides of a fish pass or weir to dissipate energy, reduce flow velocity and allow fish passage.
Bank	Land along the edge of a river or stream. Left and right refer to the bank viewed looking downstream.
Bank protection	Works to protect a bank from erosion or undermining by scour.
Barrage	A man-made structure built across a river or estuary, gated across much of its width, intended to manage flooding, aid irrigation or navigation, or to generate electricity by hydropower.
Benefits	Favourable impacts arising from an asset or project, including damages avoided.
Boater	A person who travels by boat. In this guide it includes powered and unpowered craft.
Broad-crested weir	Weir with a crest section of significant length measured in the direction of flow. For accurate flow gauging, the crest length should normally not be less than about three times the upstream head of water above the weir crest.
Bypass weir	A weir used to divert flows around a canal lock (also known as by-weir). See also *side weir*.
By-wash	A weir or sluice used to convey surplus water or control water levels upstream of a weir.
Canal	An artificial channel built or excavated for navigation, water supply, irrigation, hydropower or other purposes.

Canalised river	A river divided into reaches separated by locks and weirs, for the purpose of navigation, irrigation, flood or erosion control.
Canal side weir	A weir installed adjacent to a canal to divert some or all of the approach flow into a separate side channel.
Canoe	A small, slender boat propelled manually by a paddle. In this guide, it includes canoes (single-bladed paddle), kayaks (double-bladed paddle), stand-up paddleboards and inflatables.
Canoeist	A person who travels by canoe.
Catchment	The area of land that drains (normally naturally) to a given point on a river or drainage system.
Channel	1 The bed or course of a river or canal. 2 A navigable route through a body of water. 3 The route of the main flow through a body of water.
Coanda screen	A weir with a vertical upstream wall and sloping screen of tilted wedge wires on the downstream face that abstracts clean water and filters out fish, sediment and debris. Also known as Tyrolean weir and overflow sieve or weir.
Cofferdam	A temporary structure used to enclose a construction area, and prevent soil or water from entering into it.
Control structure	Hydraulic structure constructed across a channel or between waterbodies or channels, used to restrict the discharge passing the device and/or the water level on either side of the structure.
Conveyance	A measure of the carrying capacity of a watercourse or floodplain. A function of the flow area, shape and roughness of a channel, which can be used as a constant in a formula relating discharge capacity to channel gradient.
Crest (of weir)	Top part of weir. The level of the crest, its length and its cross-sectional shape determine the discharge (flow) characteristics of the weir.
Critical flow	Free surface flow at which the specific energy is a minimum for given discharge (and Froude number, Fr, is unity). The water depth for these conditions is known as the critical depth.
Critical velocity	The velocity at critical flow.
Current meter	Instrument for measuring flow velocity.
Crump weir	A form of weir with a precise triangular profile often used for discharge monitoring (from Crump, who defined the characteristics of this shape of weir).
Cumec	Cubic metres per second (m^3/s). A measure of rate of flow.
Dam	A man-made barrier usually built across a river to hold back water and forming a lake, or reservoir, behind it.
Dam boards	Temporary boards installed on the crest of a weir to control upstream water level (eg during periods of low flow).
Damage(s)	Adverse impacts resulting from an asset or project, eg social, economic or environmental.
Debris	Any material moved by a flowing stream.
Design flood	The discharge or flow adopted for design, usually defined in terms of return period or annual exceedance probability.
Discharge	Flow rate expressed in volume per unit time.

Discharge intensity	Discharge per unit length of weir. See also *unit discharge*.
Discharge point	The point at which abstracted water is returned to a river.
Draught	The depth of water needed to float a boat.
Duckbill weir	A weir with a crest that forms a U-shape on plan, such that the crest length is much longer than the width of the river. Similar to a horseshoe weir. The long crest gives lower variations in upstream water level for changing flow conditions, but note that this effect may not apply to flood conditions when the weir is drowned.
Drowning	In the context of weir hydraulics, a weir is said to be drowned (or drowned out) when the downstream water level rises to the point where it begins to affect flow over the weir.
Energy dissipator	A hydraulic structure to contain and concentrate the degradation of surplus energy of fast flowing water and protect the downstream bed and banks against scour.
Erosion	Process by which material forming the bed or banks of channel is removed by the action of flowing water or waves.
Estuarine	Relating to an estuary.
Estuarine barrage	A structure built in an estuary with the intention of preventing or modifying tidal propagation.
Estuary	The mouth of a river connected to the sea, where both fluvial and tidal effects occur and interact.
Failure	Inability of an asset to achieve a defined performance threshold.
Fish pass	Device provided to allow fish to migrate over or around a weir that would otherwise obstruct the movement of fish.
Fish weir	An obstruction erected in tidal waters or partially across a river to direct the passage of fish and allow them to be caught. Also known as fishing weir.
Flap gate	A straight or curved gate hinged at the base, typically moved by a hydraulic actuator at one or both sides.
Flash lock	A weir used for river navigation before the introduction of pound locks. Navigation involves removing a section of weir and winching river craft upstream through the flash of water.
Flood bank	Embankment, usually earthen, built to prevent or control the extent of flooding.
Floodplain	Land on either side of a river that is below the highest defined flood level.
Flow	Flow rate or discharge.
Fluvial	Relating to a river.
Foundation	Construction to transmit forces to the supporting ground.
Freeboard	The height of the top of a bank, floodwall or other flood defence structure. Located above the design water level to take account of physical processes that have not been allowed for in the design water level (waves etc), and an allowance for adverse uncertainty in the prediction of physical processes.
Froude number (Fr)	A dimensionless parameter representing the ratio between the inertia and gravity forces in a fluid, taking the value of unity for critical flow.
Gabion	Cuboid or tubular container made of wire mesh and filled with stones, used to form a retaining wall or provide protection against scour.
Gate	A component of a movable weir capable of being moved to give greater control over flow and water level. See also *flap gate, radial gate, sector gate, slide gate* and *vertical lift gate*.

Geomorphology	The scientific study of the process of water and sediment movement in the evolution and configuration of landforms.
Glacis	The downstream sloping face of a weir, between the weir crest and the stilling basin.
Head (of water)	The total energy of water expressed in metres of water above a datum (such as the weir crest). Note literature contains more technically precise definitions of head, making the distinction between static head, velocity head and total head
Head loss	The drop in total energy across a weir or other hydraulic structure.
Horseshoe weir	See *duckbill weir*.
Hydraulic jump	Abrupt rise in water level when flow changes from supercritical to subcritical, with associated turbulence, air entrainment and dissipation of energy.
Hydraulic structure	Structure used to control or convey flow. Structure built in a position where it may affect or be affected by flow.
Hydrograph	Graph that shows the variation with time of level or discharge of water in a river, channel or other waterbody.
Hydrology	Science of the hydrological cycle including precipitation, runoff and fluvial flooding.
Impounding	Holding back the flow of water.
Inflatable weir	Rubber tube across a river channel filled with air and/or water at low pressure to raise upstream water level.
Inspection	Visual examination of an asset for defects, usually non-destructive.
Invert level	Level of the lowest point in a natural or artificial channel.
Kayak	A small, slender boat propelled manually by a double-bladed paddle.
Knick-point recession	A sudden drop in bed level that propagates upstream in a river or watercourse by erosion of the bed.
Labyrinth weir	A weir with an elongated crest length achieved by corrugating the crest in plan view (ie multiple duckbill weirs).
Leptospirosis	An infectious disease, caused by bacteria from the urine of rats, cattle, foxes, rodents and other wild animals – rats and cattle being the most common form of transmission in the UK. The disease begins with a fever and may affect the liver or brain. It can also affect the kidneys. Also known as Weil's disease.
Listed building	A listed building is one included in a statutory list of buildings of special architectural or historic interest compiled by the Secretary of State in England.
Local scour	Scour that results directly from the impact of individual structural elements (eg piers and abutments) on the flow and occurs only in the immediate vicinity of those elements.
Lock	A structure used to raise and lower boats between stretches of water at different levels. See also *flash lock* and *pound lock*.
Main river	All watercourses shown as such on the statutory main river maps held by the Environment Agency and Defra (includes certain structures "*for controlling or regulating the flow of water into, in or out of the channel*").
Mesohabitat/ meso-scale habitat units	Broadly similar in concept to 'functional habitat' and are defined as areas where an animal can be observed for a significant portion of their diurnal routine.
Modular flow	Condition in which flow is able to discharge freely over a weir, resulting in a unique relationship between flow rate and upstream water level (modular flow occurs when the weir is not drowned).

Moment	A measure of the tendency of a force to cause a body to rotate about a specific point or axis, and can be destabilising or restoring.
Monitoring	Periodic or continuous observation and recording of asset behaviour to detect deterioration or distress, determine the extent, severity and rate of deterioration, and to determine whether a critical limit state or other criteria are at risk of being reached.
Morphology	The plan form and cross-section shape of a watercourse.
Non-modular flow	Condition in which flow is not able to discharge freely over a weir, with the downstream water level influencing the upstream level (ie drowned flow).
Nappe	The jet of water passing over a weir crest and plunging into the stilling basin. Term normally only applied where the jet is not in contact with the weir structure (ie there is an air gap between the underside of the nappe and the downstream face of the weir).
Navigation	A navigable inland waterway.
Normal depth	Depth of water in conditions of steady uniform flow.
Ogee weir	Weir with curved crest and spillway designed to match the profile beneath the nappe of water flowing over the structure, ideal for the conveyance of flood water and commonly used in reservoir spillways.
Open water swimming	Swimming in outdoor bodies of water such as rivers, lakes, or the sea. Also known as free or wild swimming.
Ordinary watercourse	Any natural watercourse not designated as a main river.
Overtopping	Water flow over a feature such as a flood defence bank, due to high water levels or waves.
Paddle and rymer weir	A manually-operated movable weir with boards (paddles) inserted between vertical timber posts (rymers).
Piping	The movement of soil particles due to water percolating through soil, leading to internal erosion.
Pound lock	A short reach of navigation with gates at both ends that control the level of water in the pound (in contrast to an earlier design with a single gate known as a flash lock).
Powered craft	A boat propelled non-manually, such as by engine, jet propulsion, sail or horse.
Radial gate	A curved skin-plate supported by radial arms and a pivot point at the centre of the arc, which is lifted to allow the passage of water. A dipping radial gate is lowered to allow the passage of water. Also known as Tainter gate.
Ramsar site	A wetland of international importance designated under the Ramsar Convention 1971.
Rapid drawdown	A rapid reduction in external water level in front of a submerged slope, sometimes leading to slope instability.
Rating curve	A relationship between flow rate and water level for a channel, weir or other hydraulic structure. Weirs with fixed crests generally have non-varying rating curves provided the flow over the weir is modular. Rating curves for natural channels may vary with time due to changes in channel geometry or to seasonal growth of vegetation. Also known as stage-discharge curve.
Reach	A length of channel between defined boundaries.
Regulator	Hydraulic structure for controlling water levels or division of flow.
Reno mattress	A structure with a large plan area and a small thickness made from wire mesh and filled with stones on site to create a flexible, permeable and monolithic structure, often used for river and canal bank protection works.

Reservoir spillway	An overflow channel to convey surplus flow over a dam.
Residual uncertainty allowance	An allowance for uncertainty in the estimation water level.
Return period	Average interval of time between years in which events occur that equal or exceed a given magnitude. Inverse of the probability that a given event will occur in any one year.
Revetment	A sloping surface of stone, concrete or other material used to protect an embankment or channel against erosion.
Riparian habitat	The zone along the banks of a river or stream, typically ecologically diverse and valued by wildlife as a source of food and shelter, as well as a corridor linking other areas.
Rip-rap	Wide-graded quarried stone placed in a random fashion as protection against erosion.
Risk	Product of probability (or likelihood) and consequences.
River	Any natural watercourse (including modified watercourses).
River weir	A structure over which water may flow, used to control the upstream water level in a watercourse, erosion and/or to measure the discharge.
Rock weir	A steep reach stabilised by rip-rap, designed to maintain biologically adequate depth and velocity conditions during low flow conditions and pass large flows with minimal structural damage. Also known as rock ramp.
Scour	Erosion resulting from the shear forces associated with flowing water or wave action.
Scour protection	Works to prevent or mitigate scour.
Sector gate	A curved skin-plate forming a part circle that rotates about a horizontal or vertical axis. Also known as rising sector gate.
Sediment	Natural granular or cohesive material (eg clay to boulders) that is transported by flowing water.
Sequent depth	Flow depth downstream of a hydraulic jump.
Sharp-crested weir	Weir with a crest section of small thickness measured in the direction of flow, typically used for measuring flow in the laboratory and small channels. For accurate flow gauging, the crest is normally chamfered with the horizontal tip having a thickness of the order of 1 mm to 2 mm.
Side weir	Weir installed in a channel to divert part of the approach flow into a separate spill channel.
Siltation	The deposition of sediment.
Slide gate	A vertical gate that opens and closes by sliding within supporting guides. Also known as a penstock gate.
Sluice (or sluice gate)	A movable gate used to control flow.
Special area of conservation	A site protected under Directive 92/43/EEC (Habitats Directive).
Special protection area	A site protected under the Directive 2009/147/EC (Wild Birds Directive) for rare and vulnerable birds and migratory species.
Specific energy	The energy of a fluid relative to bed level given by the sum of pressure and velocity heads.
Stage	Elevation of water surface relative to an established datum.
Stepped weir	A weir designed to cascade low flows with gradual energy dissipation, reducing the size of stilling basin required.

Stilling basin	Energy dissipator comprising a basin in which a hydraulic jump occurs.
Stop logs	Timber, metal or concrete boards installed in vertical grooves upstream or downstream of a structure, used to allow temporary de-watering. Also used on canals to control water loss in case of a breach.
Straight drop weir	A weir with a sharp drop immediately downstream of the crest, usually into a stilling basin. The plunging flow has a tendency to create dangerous recirculating flow in the stilling basin which can present a significant safety hazard.
Subcritical flow	Flow in a channel at less than critical velocity, at which the Froude number is less than unity, slow and deep compared to supercritical flow.
Supercritical flow	Flow in a channel at greater than critical velocity, at which the Froude number is greater than unity, typically fast and shallow.
Superflood	A flood larger than the design flood which key structures are required to survive albeit with an acceptable degree of damage. Also known as the check flood.
Supersaturation	A negative oxygen deficit in water.
Tailwater level	Water level downstream of a weir or hydraulic structure.
Tilting gate	A steel gate hinged at the bottom such that it can be raised or lowered to act as a weir with a variable crest level. Can be operated by hydraulic rams or cables.
Towback distance	The length of recirculating flow in a hydraulic jump immediately downstream of a weir.
Transverse weir	Weir installed across the width of a channel. Usually the crest line of the weir is set at right angles to the longitudinal centreline of the upstream channel, with the flow passing over the weir being discharged into the downstream reach of the channel.
Underwater inspection	Visual inspection of an asset below water level, to record existing condition and determine the profile of the river bed at the structure, upstream and downstream.
Unit discharge	Discharge per unit width of a weir or channel (averaged over a cross-section or local to a point of interest). See also *discharge intensity*.
Unpowered craft	A boat propelled manually, such as a canoe, kayak, rowing boat, stand-up paddleboard or inflatable.
Velocity head	Measure of the kinetic energy of flowing water, represented as the vertical height to which water would rise in a pitot tube.
Vertical lift gate	A vertical skin plate stiffened by horizontal beams and vertical ribs, supported by embedded channels on either side, which can be raised or lowered. May comprise a single gate, two linked sections (hook gate) or two or more independently actuated sections (multiple leaf gate).
Water level	The level of the water surface.
Watercourse	Route along which water flows.
Waterway	Channel used, previously used, or intended for the passage of vessels.
Weir	An artificial obstruction in any watercourse that results in increased water surface level upstream for some, if not all flow conditions. A structure in a river, stream, canal or drain over which free-surface flow occurs. May be used variously for control of upstream water levels, diversion of flow, and/or measurement of discharge. See also *air-regulated siphon, broad-crested weir, Crump weir, inflatable weir, ogee weir, paddle and rymer weir, rock weir, sharp-crested weir, stepped weir, straight drop weir* and *Coanda weir*.

Weired lock A navigation lock where the lock gates have been removed and a weir has been installed to control water levels.

Wing wall Wall tying a weir abutment into the river-bank, typically straight, but may be curved. May be orientated at right angles or at 45 degrees to the flow, or other appropriate angle.

Abbreviations and acronyms

ADA	Association of Drainage Authorities
ALARP	As low as reasonably practicable
AONB	Area of Outstanding Natural Beauty
ASCE	American Society of Civil Engineers
CCTV	Closed-circuit television
CDM 2015	Construction (Design and Management) Regulations 2015
CEH	Centre for Ecology and Hydrology
CFD	Computational fluid dynamics
CIfA	Chartered Institute for Archaeologists
COSHH	Control of Substances Hazardous to Health
CoW	Clerk of Works
CRoW	Countryside and Rights of Way Act 2000
CSM	Conceptual site model
DCAL	Department of Culture, Arts and Leisure
DCLG	Department for Communities and Local Government
DfT	Department for Transport
DIN	German Institute for Standardization
DOENI	Department of the Environment in Northern Ireland
EC7	Eurocode 7
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPR	Environmental Permitting Regulations
FCERM-AG	Flood and coastal erosion risk management appraisal guidance
FEA	Finite element analysis
FoS	Factor of safety
GRP	Glass-reinforced plastic
HDPE	High-density polyethylene
HER	Historic environment record
HGN	Hydropower Guidance Notes
HSE	Health and Safety Executive
HTA	Historic trend analysis
ICPDR	International Commission for the Protection of the Danube River
IDB	Internal Drainage Board
INNS	Invasive non-native species
ISO	International Organization for Standardization
LA	Local authority
LCA	Landscape character assessments
LLFA	Lead local flood authorities
LPA	Local planning authority
LVIA	Landscape and visual impact assessment

MEICA	Mechanical, electrical, instrumentation, controls, automation
MNA	Monitored Natural Attenuation
NAO	National Audit Office
NCA	National Character Areas
NDT	Non-destructive testing
NEIA	Northern Ireland Environment Agency
NGO	Non-governmental organisation
NFM	Natural flood management
NHLE	National Heritage List of England
NHPP	National Heritage Protection Plan
NIEA	Northern Ireland Environment Agency
NNSS	Non-native species secretariat
NPPF	National Planning Policy Framework
NPBV	Net present value
NRFA	National River Flow Archive
NRW	Natural Resources Wales
OART	Ouse and Adur Rivers Trust
OASIS	Online access to the index of archaeological investigations
OS	Ordnance Survey
P&R	Paddle and rymer weir
PAH	Polycyclic aromatic hydrocarbons
PCB	Polychlorinated biphenyls
PEL	Predicted effect level
POH	Persistent organic pollutants
PRAGMO	Practical River Restoration Appraisal Guidance for Monitoring Options
PRoW	Public Rights of Way
PSG	Project steering group
RBMP	River Basin Management Plan
RHS	River Habitat Survey
RCC	River Continuum Concept
RRC	River Restoration Centre
SAC	Special Area of Conservation
SAM	Scheduled Ancient Monuments
SCADA	Supervisory control and data acquisition
SEPA	Scottish Environment Protection Agency
SGV	Soil guideline values
SNH	Scottish Natural Heritage
SNIFFER	Scotland and Northern Ireland Forum for Environmental Research
SoS	Secretary of State
SPA	Special Protection Area
SPT	Standard penetration test
SSSI	Site of Specific Scientific Interest
TBTA	Thames Boating Trades Association
TEL	Threshold effect level
TPO	Tree Preservation Order

UNESCO	United Nations Educational, Scientific and Cultural Organization
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
UAV	Unmanned aerial vehicles
UXO	Unexploded ordnance
WFD	Water Framework Directive
WHS	World Heritage Sites

Notation

B	Weir crest length (m)
C	Discharge coefficient dependent on weir crest shape
h	Head over weir crest (m)
Q	Flow (m^3/s)

Part 1
Overview

1
2
3
A

1 Introduction

1.1 WHAT IS A WEIR?

A weir is an impounding structure within a watercourse over which water may flow, that increases water surface levels upstream over a range of flows.

A weir may perform one or more functions (**Figure 1.1 and Section 3.2**).

1.2 AIMS OF THE GUIDE

This guide provides good practice guidance on the design, maintenance, modification and removal of river weirs, including weirs on canalised rivers, canal by-weirs and side weirs, and river barrages. It does not cover dams, reservoir spillways, estuarine barrages or structures regulating natural lakes.

The guide replaces Rickard *et al* (2003). While comprehensive, since its publication many lessons have been learned in terms of operation and safety of weirs, and the implementation of WFD 2000 has led to a greater focus on weir removal. Although it is acknowledged that the majority of work on weirs is still carried out to maintain their current function(s), this guide leans heavily towards the alteration of weirs to benefit ecology, reflecting an industry need for greater guidance on topics such as geomorphology, environmental issues, alternatives to weirs and weir removal. The target audience includes regulatory authorities, professionals (engineering, geomorphological etc), clients, engineering consultants and contractors, architects, navigation authorities, heritage bodies, owners of mills, historic buildings or landscapes, weir preservation societies, abstraction licence holders, hydropower promoters, land owners, land agents and farmers. It is also applicable to other river and canal users and stakeholders including fisheries owners, angling clubs and recreation bodies (such as canoe or rowing clubs).

Readers will come to the guide with different perspectives, depending on the drivers for change and the questions they are trying to answer. The guide aims to direct readers towards the information that they are looking for, and to alert them to other issues that they may not be aware of. It aims to give a balanced view.

Box 1.1 Key facts about weirs

British rivers contain a large number of weirs: the Environment Agency has records of 13 000 weirs of which 12 000 are in private or unknown ownership, while the Canal & River Trust in England and Wales has records of around 170 weirs.

There are many types of weir, weir type being influenced by the function of the structure and watercourse characteristics. Regardless of their type, function, ownership, age or condition, weirs are engineering structures that have to operate in demanding environments. A weir must satisfy fundamental hydraulic, structural, environmental and health and safety performance requirements in construction, operation and maintenance, as well as following removal or failure. Weirs and their owners can face conflicting demands, and a weir which meets its functional objectives may fail to meet safety requirements (or vice versa).

People drown in weirs every year in the UK. The hydraulic hazard created by strong re-circulating currents downstream of weirs can affect visitors, particularly where a river is capable of being navigated by canoe. Weir owners have a duty of care to visitors and must manage the safety risks caused by a weir. Sadly, the wider uses of rivers and safety of river users was often not considered in the past.

Weirs can intervene in watercourses, their natural processes and the ecosystem services that they provide. Although they can provide habitat, weirs can delay fish and eel migration, leading to sparse populations upstream. Slow flow and sediment deposition in the impounded reach upstream of a weir affects water quality, habitat diversity and geomorphological condition, with impacts on flora and fauna. Restricted sediment transport to downstream can cause erosion.

Weirs may be of historical significance, either on their own, as part of a historic water management system (such as a mill or lock) or by contributing to the aesthetic setting or soundscape of a heritage asset. Many weirs in the UK are up to 300 years old and fishing weirs date back to Neolithic times.

The removal of unnecessary weirs can reduce maintenance costs, improve upstream migration of fish and eels, and restore sediment continuity, helping to meet the Directive 2000/60/EC (WFD Directive) targets. The decision to remove a weir depends on its function and potential impacts on economics, property, structures, aquatic ecology or dependent wetland habitats. Lowering or removal can release contaminated sediment trapped upstream of the weir, with potentially harmful effects on water quality and the environment.

If complete removal is not feasible then partial removal, lowering or bypassing could be considered. Alternatives to weirs can also be considered where impoundment is essential.

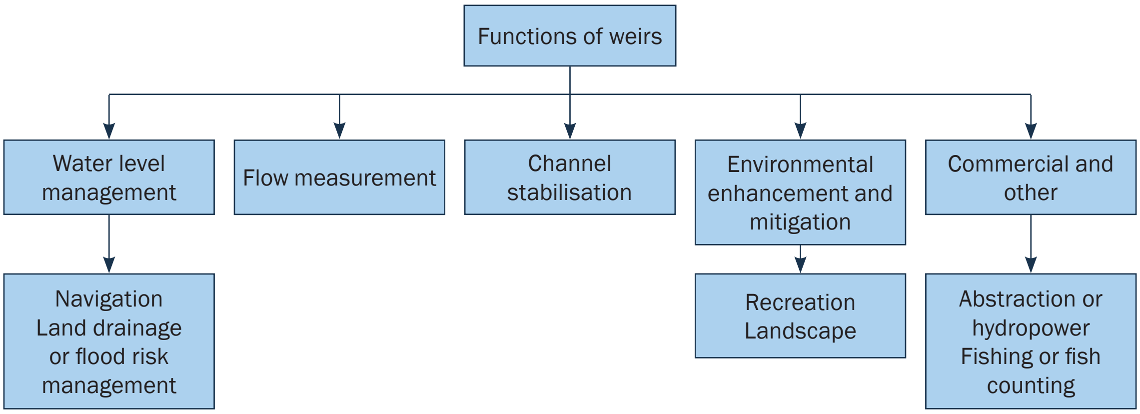

Figure 1.1 Functions of weirs

1.3 ABOUT THIS GUIDE

This guide leads the reader through the process of managing weirs and is presented in three parts, aimed at readers with different starting points and questions (**Figure 1.2**).

The guide covers:

- Understanding the function/s of a weir and setting appropriate project objectives
- Legal and policy requirements.
- Multi-disciplinary and multi-stakeholder interests (safety, operational, environmental, historical, recreational, commercial).
- Types of weir.
- Assessing whether a weir is the most appropriate option and whether alternatives to weirs could be adopted.
- Where a weir is no longer necessary, how to plan and implement its removal or modification.
- Where a weir cannot be removed, how to assess and improve safety, environmental and operational performance by refurbishment or modification, and risk-based asset management.
- Where a new or replacement weir is necessary, how to design a new or replacement weir.

The sections that are likely to be of greatest relevant to the reader will depend on whether the reader is considering the removal of a weir, the refurbishment, repair or improvement of an existing weir, or the construction of a new or replacement weir (**Figure 1.3**). Examples and case studies are given in boxes throughout, with detailed case studies in **Appendix A3**.

Each chapter generally follows the structure:

- **Principles:** a brief overview of the topic.
- **Issues:** discussion of the range of issues and perspectives, with signposting to external guidance or a cross-reference to detailed guidance in methods sections.
- **Methods:** detailed guidance where this is not readily available elsewhere.
- **References:** at the end of each chapter.

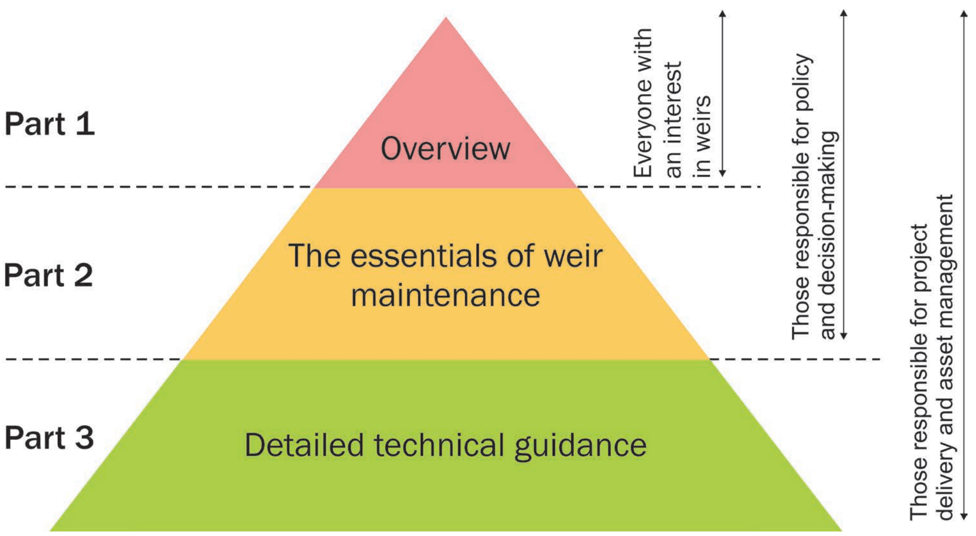

Figure 1.2 Overview of guide

The level of detail varies between sections and topics according to the maturity of existing guidance. Where science or evidence is emergent and/or controversial, the guide provides general pointers on emergent good practice, but does not seek to create new knowledge or reconcile all controversies. Where information exists but is presently disparate, this guide brings together guidance into a single non-contradictory source. Where recognised, authoritative and accessible guidance already exists, the guide signposts this rather than reproduce existing guidance.

Summary of weir management	Chapter 1: Introduction Chapter 2: Guidance framework
What is needed to inform policy, make decisions and guide others?	Chapter 3 What are the objectives? Chapter 4 Is there a need to intervene? Chapter 5 What are the options? Chapter 6 How should the options be compared? Chapter 7 Design, implementation and monitoring
3 What are the legal issues affecting weirs and weir owners?	Chapter 9 Law and policy Chapter 10 Operational safety Chapter 11 Natural and historic environment
4 How do organisations comply with the WFD?	Chapter 5 What are the options? Chapter 9 Law and policy Chapter 11 Natural and historic environment
5 How can fish passege, habitat or water quality be improved?	Chapter 5 What are the options? Chapter 11 Natural and historic environment
6 What safety issues should be addressed due to weirs?	Chapter 10 Operational safety
7 How can organisations inspect/,maintain weirs?	Chapter 8 Asset management
How can organisations deal with a damaged weirs?	Chapter 5 What are the options? Chapter 8 Asset management Chapter 14 Foundations and geotechnical design
What are the issues surrounding weir failure, removal or modification?	Chapter 5 What are the options? Chapter 9 Law and policy Chapter 11 Natural and historic environment Chapter 12 Geomorphology
How do organisations design and implement new weirs or changes to existing weirs?	Chapter 12 Geomorphology Chapter 13 Hydrology and hydraulics Chapter 14 Foundations and geotechnical design Chapter 15 Construction
Case studies and lessons learnt	A3 Case studies

Figure 1.3 Route map

2 Guidance framework

2.1 INTRODUCTION

The asset management cycle is iterative and involves periodic review of objectives and the need to intervene, possibly because of drivers for change such as safety concerns, defects identified during an inspection or changes in legislation (**Figure 2.1**). If there is no need to intervene, then inspection, maintenance and any routine monitoring can continue as usual, adapted in light of the findings of previous inspections. If there is a need to intervene, consideration should be given to identifying and comparing options (whether construction, refurbishment, modification, demolition or removal). Design and implementation may be followed by post-scheme monitoring.

2.2 WHAT ARE THE OBJECTIVES?

The first step in the decision-making process is to define the present functions and future objectives for a weir, watercourse, catchment or site (**Chapter 3**). These may be related to legal or policy requirements, the present or intended function/s of a weir (eg water level management, flow measurement, channel stabilisation, environmental enhancement or mitigation, or commercial), health and safety, hydraulics or structural performance.

There may be drivers for change such as safety concerns or legal or policy requirements. The weir

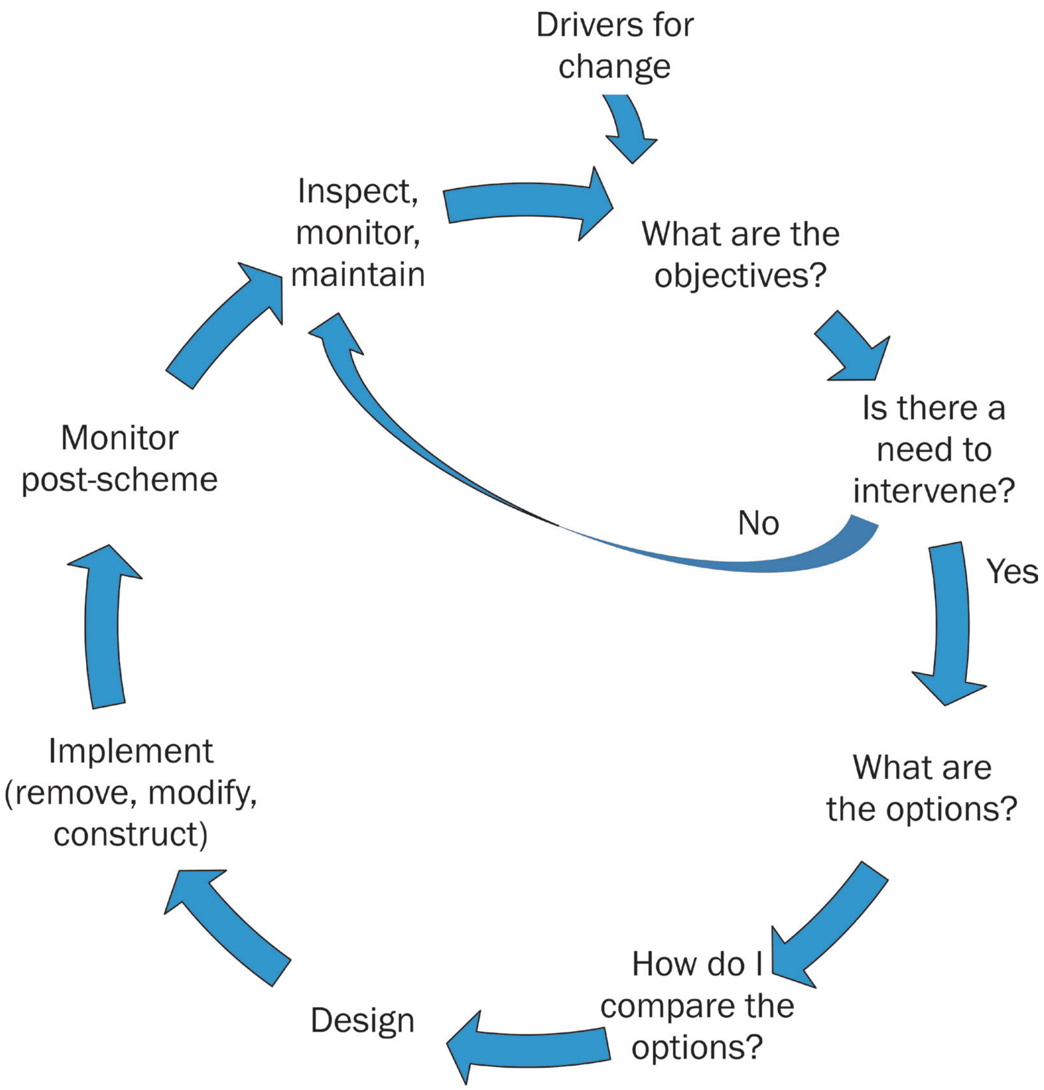

Figure 2.1 Weir management cycle

may have suffered damage following a flood or may not be performing as required. Alternatively, the function of the weir or funding may have changed. There may be opportunities to install hydropower, develop recreation facilities, improve the environment or adopt new technology (**Section 3.2**).

Data gathering should support the process and may include a desk study of existing information, site walkover, surveys and ground investigation. It is important to allow sufficient lead time for environmental baseline surveys as some can only be undertaken at certain times of the year, and consider the timings of different activities. For example, recreation may be seasonal or take place in the evenings or at the weekend rather than during the working day (**Section 3.3**).

There are many issues and interests to be considered when planning and implementing works on weirs and it is difficult to design works on weirs that will fully satisfy the aspirations of all interested parties of the weir or the reach of river in which it is located. Inevitably there will be instances where there are conflicts of interest. With proper maintenance and periodic rehabilitation works, a new or replacement weir structure may have a useful life of between 50 and 200 years and design decisions taken now may last for several generations. It is important that those responsible for weirs are aware of all of the issues and potential conflicts, and consult stakeholders in order to seek the best solution (**Section 3.4**).

Box 2.1 The importance of consultation

Works to weirs can affect several generations. It is important to consult interested parties and involve engineers, ecologists and geomorphologists, both in the decision to build a new weir, and also during planning and design, so that opportunities for good practice are taken.

2.3 IS THERE A NEED TO INTERVENE?

The need to intervene will depend on whether a weir meets its objectives. If a weir no longer performs a function, or its present or intended function has changed such that the present design is no longer necessary, it may be fulfilled by means other than a weir (**Chapter 4**).

Identify potential impacts, benefits, issues and opportunities in the permanent and temporary conditions (**Section 4.2**). These may relate to safety (**Chapter 10**), the environment (**Chapter 11**) or geomorphology (**Chapter 12**). There may also be impacts on hydraulics (**Chapter 13**), land drainage and flood risk, hydropower or contribution to renewable energy targets. They may be affected by aspects such as access, utilities, ground conditions, river type, flow variability, risk of flooding, river sediment size and level of contamination, and environmental constraints such as designated sites or protected species.

2.4 WHAT ARE THE OPTIONS?

If there is need to intervene, the weir owner or manager should consider whether the weir is still needed, or whether it could be removed, modified or replaced by an alternative to improve achievement of WFD targets.

A guide to the types of weir is given in **Chapter 5** along with alternatives to impounding weirs that can give the desired outcomes without the need for a weir structure.

If an existing weir no longer has a function, it may be possible to remove, lower, modify or bypass the weir if the environmental impacts are acceptable or can be mitigated. This can reduce or eliminate a maintenance burden, health, safety and environmental risk. Allowing a weir to fail naturally is generally less desirable than controlled intervention and can have adverse impacts due to the uncontrolled release of sediment downstream, which may be contaminated. Action may be required to avoid flooding or pollution, or to safeguard structures downstream (**Section 5.3**).

Where a weir needs to be retained (eg for abstraction or monitoring purposes), it may need repair or modification to secure its continued performance and/or mitigate for environmental impacts or safety concerns. This may involve adding a fish or eel pass, cutting a notch in the crest or retrofitting baffles to the apron to break up the recirculating flow and reduce hazard, although care is needed to ensure that baffles do not create an entrapment hazard (see **Section 5.4**).

New or replacement weirs are discussed in **Section 5.5**. Types of weir, their advantages and disadvantages are discussed in **Section 5.2**. More detailed information is given in **Appendix A1**.

Regardless of the approach taken, options should aim to work with natural processes and perform the functions of a weir without compromising other interests. Options should have regard to changes that may take place during the design life of the weir such as climate, land use or land management, and consider how to deal with them. This may involve selecting options that are sufficiently robust to accommodate a range of future scenarios, flexible to allow alteration to new circumstances in the future, or capable of phased implementation so that inflexible measures can be delayed in anticipation of better information.

2.5 COMPARING THE OPTIONS

Option appraisal involves assessing whether options meet the project objectives and comparing these to select one. The method of appraisal depends on the size, complexity and risk associated with the project. The level of detail generally increases as the work progresses and the number of options is refined. The process involves technical, environmental and economic appraisal and is generally iterative – options are developed

Table 2.1 Key issues during design, implementation and monitoring

Topic	Key issues
Future-proofing (**Section 7.2.10**)	Potential changes over design life of weir. Method of eventual decommissioning.
Operation and maintenance (**Chapter 8**)	Safe access to and from the weir, walking surfaces, edge protection and task lighting. Monitoring to inform decision making or as a condition of consent.
Safety (**Chapter 10**)	Hydraulic, physical, chemical or biological hazards. Safe access for inspection, maintenance and operation. Safety of users of the river or river-banks. Ease of rescue from hydraulic jump below weir.
Environment (**Chapter 11**)	The need for fish or eel passes, or otter ramps. Restoration of natural processes within channel after removal. Lateral connectivity between river and floodplain. Recreational enhancement for canoeists, anglers, walkers and open water swimmers. The impact on the historic environment.
Geomorphology (**Chapter 12**)	Viability of alternatives to a weir. For new or replacement weirs, location where bed and banks are likely to remain stable, minimising weir height and impounded length, encouraging sediment transport by providing upstream sloping face. Weir alignment, impact on habitat or nearby structures (eg scour). Weir pool dynamics.
Hydrology and hydraulics (**Chapter 13**)	Assessment of design flows (flood and low flows). Water level during low flow conditions. Hydraulic conditions, afflux and flood risk during high flows. Wing walls to direct flood flows over weir and promote smooth flow transition between river-bank and weir. Scour due to turbulent flow at the base of a weir. Also, the need for energy dissipation, scour protection and foundation design deeper than the predicted scour depth, either by embedding the downstream cut-off or by providing a weir toe. Level of walkways and bridges relative to flood level.
Geotechnical, structural and material design (**Chapter 14**)	National and international standards and guidance. Resistance to seepage, piping and uplift. Selection of materials that are durable, economic and in keeping with the desired visual appearance of the weir.
Implementation (**Chapter 15**)	Early involvement of construction professionals. Funding and procurement. Risk allocation. Access for plant, labour, materials and waste. Temporary works and integration into permanent works. Timing of construction. Management of construction flood risk and public safety. Environmental mitigation of construction activities. Post-scheme monitoring.

and refined as they are compared with objectives, opportunities and constraints, and accommodate feedback from any engagement process.

Technical appraisal identifies which options are technically viable, with regard to hydrology, hydraulics, structures, geotechnical or other aspects of engineering (**Section 6.2**).

Environmental appraisal identifies the options that have acceptable impacts on the environment or impacts that can be mitigated to an acceptable level (**Section 6.3**). An appraisal should consider all of the impacts, benefits, issues and opportunities of each option, including those affecting the wider catchment, not just the weir and its immediate environment. This will be guided by many factors such as ecology (**Sections 11.5 and 11.6**), geomorphology (**Section 12.3**), heritage (**Section 11.8**), constraints involved in the management of the structure, as well as existing law and policy, in particular the WFD (see **Chapter 9**).

Economic or financial appraisal compares the remaining viable options to determine which give the most favourable outcomes over the life of the asset (**Section 6.4**). Cost and (where applicable) revenue estimates should be prepared at an early stage to support the business case for doing something and to allow the project promoter to secure funding or financing in good time. An ecosystems approach or similar can take account of environmental impacts that may be difficult to quantify.

Finally, a preferred option should be identified. Keeping a record of all options considered and eliminated can provide an invaluable audit trail when justifying the acceptance or rejection of an option with stakeholders later on.

2.6 DESIGN, IMPLEMENTATION AND MONITORING

Key issues that need to be considered during design, implementation and monitoring are summarised in **Table 2.1** with further guidance in **Chapter 7**.

Consent for work in watercourses will be dependent on demonstrating compliance with the WFD and other environmental legislation. The legal and policy framework affecting weirs is covered in **Chapter 9** and common consent requirements are discussed in **Section 9.7**.

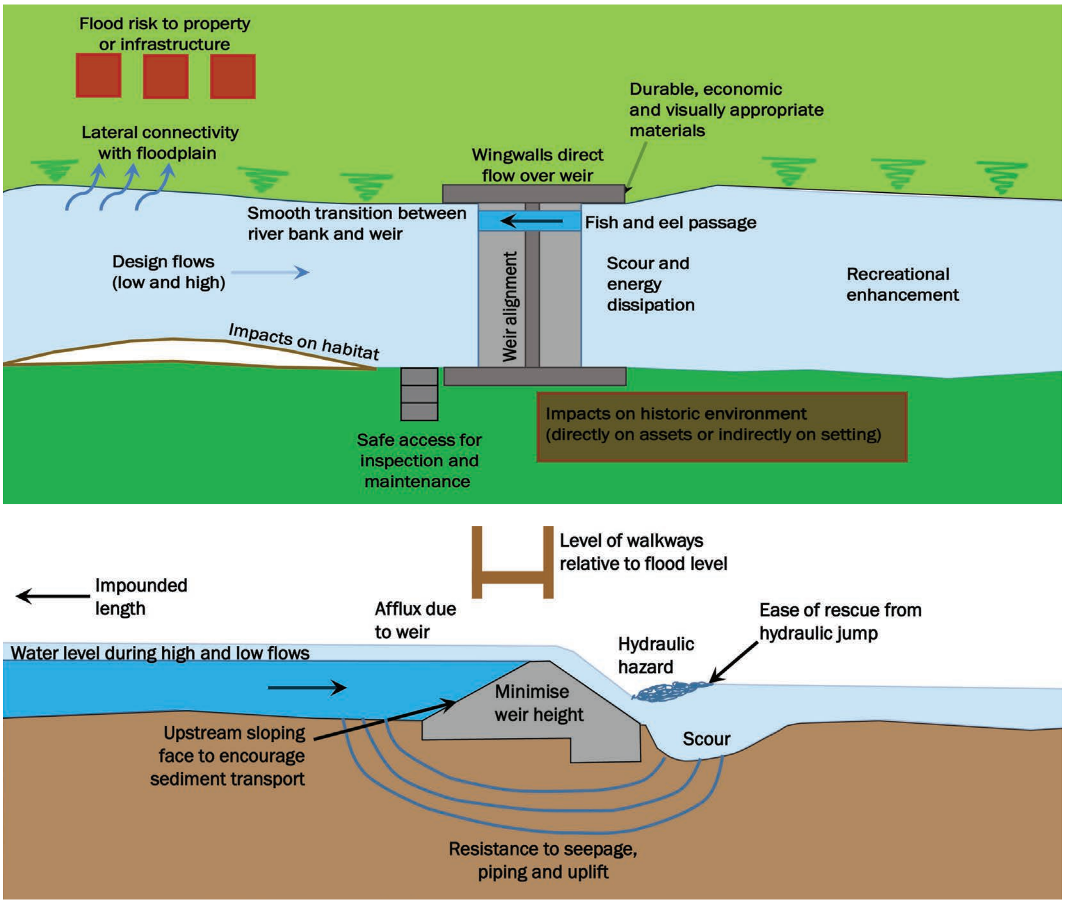

Figure 2.2 Key issues during design, implementation and monitoring

Part 2
Essentials of weir management

1

2

3

A

3 What are the objectives?

3.1 INTRODUCTION

The first step in the decision-making process is to define the objectives (or functional requirements) for a weir, watercourse, catchment or site (**Section 3.2**). These will be influenced by the history and context of a site, its present functions (**Table 3.1**), drivers for change, and future aspirations of stakeholders. The process will involve data gathering (**Section 3.3**) and consultation (**Section 3.4**).

Drivers for change may include:

- damage due to hydraulic action, scour or debris impact (**Chapter 8**)
- legal or policy requirements (**Chapter 9**)
- safety concerns following a risk assessment, accident or near miss (**Chapter 10**)
- shortfall in performance
- change in functional requirements
- change in funding
- technological developments
- opportunities to install hydropower, develop recreation facilities or improve the environment.

Typical objectives affecting weirs are given in **Table 3.2**. Each aspect is discussed in more detail in the sections that follow.

Box 3.1 Objectives for the improvement of an existing weir

A 120-year old weir in an urban area was in poor condition and objectives were defined during stakeholder engagement. A primary stakeholder wished to secure water supply to an industrial site, which was a major local employer, and reduce scour, sedimentation and debris accumulation (and future maintenance).

Other stakeholders aspired to improve flow conditions for fish and eel passage through the existing fish pass and over the weir, and improve sediment transport over the weir to reduce the risk of sediment blocking the fish pass. There was also a need to avoid increasing upstream flood risk.

Table 3.1 Typical functions of weirs

Aspect	Service
Water level management (**Section 3.2.1**)	Impound water for navigation. Manage water levels (river or groundwater) for land drainage or flood risk management (eg to divert water to an offline flood storage area).
Flow measurement (**Section 3.2.2**)	Provide a unique stage-discharge relationship for many flow conditions.
Channel stabilisation (**Section 3.2.3**)	Dissipate energy at a defined location or manage water levels for stability of riverside structures.
Environmental enhancement and mitigation (**Section 3.2.4**)	Divert water to wetlands, provide habitat diversity or improve water quality and ecology. Recreation (eg provide opportunities public access, angling, boating, safe passage or challenging white water for canoeists). Landscape (eg provide an attractive riverside to support property prices).
Commercial and other (**Section 3.2.5**)	Impound water for abstraction or hydropower. Fish counting or fishing for human use.

Table 3.2 Typical weir management objectives

Aspect	Service
Operational safety (**Section 3.3.1, Chapter 10**)	Eliminate or reduce health and safety risks to visitors during construction, operation, inspection, maintenance or removal.
Natural and historic environment (**Section 3.3.2, Chapter 11**)	Avoid obstructing fish and eel passage. Conserve or restore natural or built heritage. Preserve and better reveal historic significance, often within a designed landscape or industrial archaeological context. Avoid adverse impacts.
Geomorphology (**Section 3.3.3, Chapter 12**)	Provide sediment continuity along the watercourse. Avoid undesirable scour or sedimentation.
Hydrology and hydraulics (**Section 3.3.4, Chapter 13**)	Provide the desired hydraulic performance throughout the full range of flow conditions, from low to flood flows.
Structural (**Section 3.3.5, Chapter 14**)	Resist imposed loads (or actions) due to hydrostatic pressure, hydrodynamic forces and debris impact, throughout its design life, without the need for excessive maintenance. Limit damage during a flood that exceeds the design flood. Maintain a specified condition.

3.2 FUNCTIONS OF WEIRS

3.2.1 Water level management

Navigation

In the UK, navigation weirs on rivers and canals were typically built during the heyday of canal construction (late 1700s to mid-1800s) to create level reaches of water (or pounds) between two locks. Locks (or pound locks) are used to raise and lower boats between stretches of water at different levels. Early flash locks on rivers involved removing a section of weir and winching river craft upstream through the resulting flash of water.

Weirs on navigable rivers are designed to maintain water levels which allow navigation. Many rivers would be unnavigable for much of the year without the increased depth of water provided by weirs. Many are owned and maintained by navigation authorities, particularly the Canal & River Trust, the Environment Agency, Scottish Canals and Waterways Ireland.

These weirs are often substantial structures, up to 100 m long and raising water levels by up to three metres on the upstream side. They are typically constructed from a mixture of masonry and timber with recent refurbishment being undertaken with concrete and steel sheet piles (**Case study A3.14**). They may incorporate fish passes, movable gates and flow control devices.

Remedial works tend to be restricted to summer periods when river flows are low, although emergency works may have to be carried out in more challenging flow conditions.

On canals, side weirs are used to remove surplus water from the system or to transfer water from one pound to another. Side weirs are located in the side of the waterway and have a crest level set slightly above normal water level in the canal. When there is surplus water in the pound, either due to precipitation or operation of a lock upstream, the water level rises in response and the side weir starts to operate. Flow is discharged into a local stream or drainage channel or back into a lower pound. Side weirs are similar to in-line weirs in many respects, although their hydraulic performance is more difficult to analyse (May *et al*, 2003).

Flow in canals varies seasonally depending on inflows, evaporation and the number of boat movements through locks, although the fluctuation in flow is less on a canal than for a river.

A primary requirement of navigation weirs, regardless of type or location, is to limit fluctuations in water level to maintain sufficient draught (above and below water). Overtopping of the canal embankment should be avoided as this can lead to external erosion and breach. Water level regulation can be achieved by using a long weir crest or a labyrinth weir (which allows a long crest to be accommodated into a shorter width of channel) (**Section 5.2.1**). Weir gates allow the regulation of water level and temporary timber weir boards (or 'summer-boards') can improve water level control at different times of the year.

Hydraulic performance can be affected by floating debris accumulation, seasonal vegetation growth or sedimentation at weir boards or trash screens. The discharge of surplus water can be affected by incompatible combinations of weir length and downstream culvert capacity or downstream river flood levels (ie the weir can pass more flow than can be accepted downstream).

The design and operation of navigation weirs should consider the safety of boaters, and other river and towpath users, as well as those responsible for inspection and maintenance. User safety and access restrictions are particular considerations for weirs located beneath the towpath. Navigation weirs should be resistant to boat impact. Consideration should also be given to the consequences of gate failure in the closed or open position (loss of navigation or increased flood risk).

Typical issues with navigation weirs include damaged and irregular crests, local scour (due to hydraulic action or boat movements), scour behind wing walls, and maintenance and repair of downstream aprons. Remedial works carried out in the maintenance and improvement of navigation weirs often include:

- weir crest repair and cleaning
- increasing discharge capacity by extending the crest length of side weirs and providing new outfall culverts with equivalent capacity
- reducing water level variation at locks by providing labyrinth weirs and/or sluices
- addition or refurbishment of sluices to allow water level to be lowered so that the weir crest can be inspected in dry conditions
- stabilising erosion damage using steel sheet piling or underpinning
- scour protection downstream of weirs.

Land drainage or flood risk management

Weirs can contribute to land drainage and flood risk management. They can control water levels within a watercourse (and groundwater levels), raise water levels to divert flows into offline flood storage areas or lower water levels during a flood event to increase the conveyance of the river channel (eg the River Thames weirs).

A fixed weir may be designed with an overlong crest (oblique, parabolic or labyrinth) to convey higher flows with limited variation in water level, with additional benefits for navigation. Movable weirs allow upstream water levels to be managed when flows reach a given threshold or flood storage to be activated around the flood peak. The use of movable weirs for flood risk management has a long history, with temporary boards installed and removed with the seasons to maintain river levels in the summer and allow the passage of high flows along a watercourse during the winter (see **Case study A1.13**) (see **Section 5.2**).

An essential feature of movable weirs is the ability to monitor water levels upstream and downstream to inform operation. Moveable weirs may be operated on site or remotely from a control room, if telemetry and control equipment is available to transmit data and actuate the gates. However, visual and audible warnings should be used with remote operation. Gates should be operated in a controlled manner, without creating a surge of water that could affect people or fauna.

During design there are several things to consider:

- design capacity and water levels
- the provision of water level monitoring and telemetry
- on site or remote operation
- manual operation or automated (either now or in the future)
- operating rules and sequence of operation
- safety of people and fauna
- location of power supply and its resilience to flooding
- access and operation during flood conditions
- access for routine maintenance and testing (eg lubrication)
- provision for major maintenance (eg stop log grooves)
- redundancy (eg local generator, manual operation).

Provision should also be made for blockage removal, either debris accumulation on the crest, which reduces discharge capacity, or a blockage that renders a movable gate in the open or closed position.

3.2.2 Flow measurement

Measuring the rate of flow in a river channel may be necessary for a variety of reasons. Flow information might be required for operational purposes, for instance, to provide alerts and

warnings to those at risk of flooding or to monitor the fair use of licenced water abstractions. A long-term record of flows is also often used for strategic catchment management and water resources planning. This record may be used to predict future flow patterns, flooding and droughts and to monitor the long-term behaviour of a river as it responds to changes in the environment, eg increased urban runoff, or adaptation in land-use, climate or geomorphology. Flow information obtained by gauging stations is also an important component of engineering design for most structures in or close to a river environment. Most gauging stations now provide continuous flow data using telemetry allowing continuous real time data to be collected and analysed for flood forecasting and warning during a flood event and to provide information for management of other flood regulation structures during the event.

Weirs have been commonly used for flow measurement and flow gauging weirs form a significant part of the UKs hydrometric system. The National River Flow Archive (NRFA) is the UKs focal point for hydrometric data from gauging station networks and lists the types of gauging weir that are often encountered along with typical pictorial examples. Two types of flow gauging weir used in the field are the triangular profile Crump weirs and flat-V weirs.

Gauged flows are derived by measuring water levels and calculating the related flow either by calibration of a stage-discharge relationship for the weir, or through the use of weir structures of standard geometry for which the theoretical curve has been well established by past experience and from detailed studies in the field and laboratory. Standard gauging weirs are an accurate way to measure flows in a river without the need for calibration, provided they are carefully constructed and established experimental ranges are followed. While any weir can be used to obtain information on flow, weirs that have not been designed for flow measurement will do so to a lower accuracy unless careful calibration is carried out.

Ideally flow gauging weirs should be sufficiently accurate over the full range of flows experienced in a river and for the different purposes for which the data collected will be used. However, this is not always practical. Some have been designed for accuracy at low to medium flows, for example in water resources planning, but may be bypassed at flood flows. Conversely others have been designed for high flow monitoring, for example in flood forecasting, and their accuracy for low flow measurement may be poor.

In contrast to many weirs constructed for industrial functions in the nineteenth century, many flow gauging weirs are relatively new having been constructed over the last 50 years or so to improve the extent of the hydrometric system.

Challenges currently associated with the UKs stock of gauging weirs relate to moving towards a hydrometric network, which minimises morphological and biological impacts, but

Note

This is used for flood warning and to trigger upstream gate operation to divert flows into the adjacent flood detention basin (Caldecotte Lake)

Figure 3.1 ***Triangular profile flat-V gauging weir on the River Ouzel at Milton Keynes***

produces an acceptable quality and accuracy of data (River Restoration Centre, RRC, 2013). Alteration or removal of gauging weirs requires careful consideration because of the value of the consistent long-term flow record that many gauging weirs provide. The value of the particular gauge should be considered against the benefits that may result from its removal or alteration. In some cases existing gauging weirs may not be of particular value or alternative less intrusive gauging methods may be appropriate (see **Section 5.2**).

Applying the WFD means that the construction of new flow gauging weirs may not be the preferred option for flow measurement in the future. However, there remain situations where weirs may be suitable, particularly where combined with non-intrusive methods. For example, a low head gauging weir may be appropriate for accurate low flow measurement, which can be difficult with other methods, while flood flow measurement at the gauge could use a non-intrusive method such as ultrasonics (**Figure 3.2**).

WFD improvements to existing gauging weirs are sometimes possible without affecting their flow measurement function and are dependent on the degree of impact of the weir, for example by retrofitting fish and eel passes (see **Boxes 5.8 and 13.2**).

3.2.3 Channel stabilisation

In reaches of river where the channel gradient is steep, and where erosion is an issue, the increased water depths caused by an impounding weir will slacken the water surface slopes, reduce and regulate velocities and help control sediment transport and erosion. This is done by focusing energy loss onto the weir structure, which is designed to resist damage. Such weirs are more common in other parts of the world than in the UK. For example, they are used on major international irrigation systems to regulate flow velocities and prevent erosion in canals, or when river reaches are shortened and it is desired to maintain a similar gradient of flow.

Bed degradation is a general lowering of bed level along the length of the main deepwater channel. Grade control weirs can be constructed downstream of existing structures such as bridges considered to be at risk from bed degradation, particularly where a step reduction in bed level cuts its way upstream (termed a knick-point recession, see **Figure 3.3**).

In the UK, the channel stabilisation function of a weir is usually the result of its long presence in the river channel rather than a primary function of the structure. Typically a river will

Figure 3.2 Gauging station with a Crump weir for low flow measurement and ultrasonics for high flow measurement at Market Rasen Racecourse, Lincolnshire (courtesy Andy Kirby)

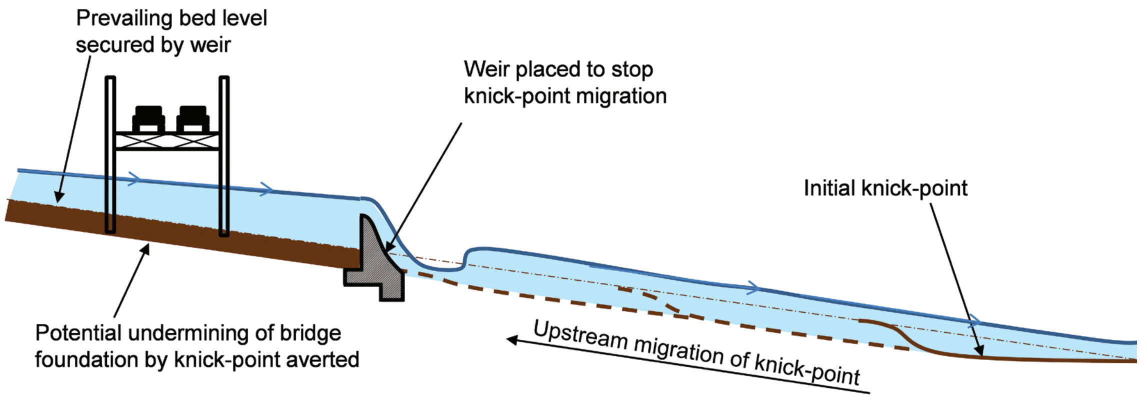

Figure 3.3 ***Constructing a weir to halt knick-point recession***

have developed a regime condition with the weir in place and river structures including bridges, buried services, channel walls/banks and drainage systems will have been designed for the prevailing water and bed levels. So, the channel stabilisation function of an existing weir is a significant consideration for weir removal projects, where upstream structures may rely on the weir's presence for their continued stability.

Where check weirs are installed to manage an over-steep channel, consideration should be given to the design life of the structures. **Case study A3.3** is a good example of a project where check weirs have failed and the underlying problem of an over-steep channel remains.

3.2.4 Environmental enhancement and mitigation

Weirs are artificial structures and generally seen to detract from, rather than enhance, the natural environment, particularly following implementation of the WFD.

However, weirs can enhance the landscape and provide opportunities to create water meadows or wetland and conservation habitats. They can raise water levels to prevent the river channel drying out upstream, control water levels or divert flow into wetlands (although an intermittently dry channel can provide habitat for some species). Aeration of the river water as it cascades over the weir crest can assist oxygenation of the water at this point as the concentrated gradient and removal of natural features upstream will reduce aeration opportunities. A weir can also limit sediment conveyance and prevent the migration of fish upstream and downstream. This limits their access to suitable spawning sites, reduces the overall biological value of a fishery and prevents recolonisation following a pollution incident. The impounded reach upstream of a weir creates a more uniform habitat, with lower biodiversity than a natural river, which can offer benefits as an ark site (safe haven) for certain recovering species (eg white clawed crayfish), but may also be exploited by invasive species. Impounded water may have lower oxygen levels and higher concentrations of other dissolved gases. Alternatives may exist to create the desired water level rising, eg through narrowing of the channel (see **Section 5.2.3** for alternatives to weir structures).

Recreation

For recreational water users such as canoeists, rafters or rowers, weirs can provide challenging white water conditions or a life-threatening hazard. White water inevitably involves some risk, but properly engineered, the risks can be reduced without losing the excitement. Swimmers, particularly adventurous children, are also attracted to weirs during warm weather, and may use them as a water slide or diving board.

Asset owners should consider the safety of weirs, especially if the river is known to be used for recreation. Failure to do so may render those responsible liable to prosecution in the event of an accident. In some cases, existing weirs that do not provide safe or suitable conditions can be modified (see **Chapters 10 and 11**). When new weirs are constructed, it is important that the potential interests of land and water users are considered in the planning and design process.

Historically, weirs have also been installed to maintain water levels and depth for fish holding areas and angling amenity, particularly in catchments prone to low flows, although weirs are less commonly installed for such purposes now.

Landscape

Weirs may be perceived as a close second to bridges in their importance in the river scene and can contribute to the creation of niche environments and vistas within designed landscapes, such as parks and gardens. A weir may create a reflecting pool upstream, the weir plan form or profile may be dramatic or a series of weirs may form a cascade. The sound of water can be adverse or beneficial, depending on location and land use.

Greater emphasis has been placed on the value of the natural environment by the WFD and there is a move towards promoting weir removal, and restoration of natural profiles. Landscape and visual benefits/disbenefits of weir construction or removal need to be balanced alongside heritage and wider environmental implications. These complex interactions of interests need to be understood, acknowledging, for example, the value of a historically significant structure or waterbody, and the associated recreational or commercial activities. The decision-making process relating to weir construction, removal or modification depends not only on the forecast physical, biological and economic outcomes, but also public perceptions of the future aesthetics and use of the resulting landscape. Weirs often combine landscape and heritage issues and it is important to consider the setting of a weir before making any changes.

3.2.5 Commercial and other

Abstraction or hydropower

Abstraction generally requires a head of water to drive flow along a water supply channel or pipeline, which is typically provided by installing a weir to impound water although alternative methods are available (**Section 5.2.3**, and SEPA, 2008). The differential head across a weir offers a useful opportunity to harness potential energy for the purpose of power generation and historic weirs were often constructed to supply watermills. These form integral parts of watermill and historic industrial landscapes. In these contexts, they can be significant features contributing to local character in urban and rural settings, along with their water supply and flow control features, such as mill leats (headrace canals), tailrace canals, aqueducts and sluices.

Non-consumptive abstraction (eg for hydropower) reduces river flows in the depleted reach between the abstraction point and discharge point, while consumptive abstraction (eg for irrigation, industry or drinking water) removes water downstream of the abstraction point (although a good proportion may be returned by industry and sewage works). Abstracted flows are sometimes diverted between catchments and discharged into another watercourse, supplementing natural flows and creating a 'compounded' reach carrying additional water.

There are biosecurity issues surrounding inter-basin transfer, especially those with white-clawed crayfish or salmon. Key issues with abstraction include the protection of low flows, high flows and flow variability. It is also important to provide sufficient attraction flow for upstream migrating fish and spawning, and ensure sediment is still transported downstream. Abstractions exceeding 20 m^3 per day must be screened to protect eels.

Continuity for fish is important and a fish pass may be required. The need for screening and type of screen depends on the purpose of the abstraction and the type of equipment used. For example, a fish screen may be required at the abstraction point (and possibly the discharge point) to prevent harm to fish and eels, and/or to prevent debris from entering the abstraction flow and causing blockage or damage to equipment.

Fishing and fish counting

Weirs can also be used to assist with fish counting, in conjunction with traps on fish passes or smolt (young fish) chutes that are emptied regularly, or optical, resistive or hydroacoustic counters.

Fishing weirs on rivers, lakes or tidal waters aim to trap fish as they attempt to swim upstream or eels as they migrate downstream, or re-direct fish elsewhere, such as a fish ladder. This practice dates back some 8000 years and they are historically significant as a record of ancient fishing activity. Typically constructed from V-shaped basketwork, some of these structures remain due to waterlogging and they are best identified from the air.

3.3 WEIR MANAGEMENT OBJECTIVES

3.3.1 Operational safety

Often there are conflicting demands on a weir and a weir that performs well in many respects may present a safety hazard to people, animals or birds. The hazards due to weirs can be hydraulic, physical, chemical and biological. The greatest hydraulic hazard is the strong re-circulating flow downstream which looks harmless because the water surface is relatively flat. This is often accompanied by reduced buoyancy due to aeration of turbulent flow and suction currents into sluices and by-washes.

Weir owners have a duty of care to visitors and should manage the safety risks caused by a weir as far upstream and downstream as they have property rights. Beyond this, they should inform other affected property owners of the known hazards associated with the weir and its operations.

A risk assessment should identify the hazards at a weir, the people who may be harmed, likelihood of them coming to harm and ease of rescue if they get into difficulty. This should be reviewed periodically, with more frequent assessments if there is a serious incident or accident, changes to the site or before works to the weir.

If the risk presented by a weir is unacceptable, it should be mitigated, ideally by eliminating or reducing it. If this is not possible, consideration should be given to reducing the probability of someone entering the weir from land or water or facilitating rescue. The approach taken depends on factors such as access to the weir from land and/or water and by whom, conditions at the waterside, and the presence of hidden hazards.

3.3.2 Natural and historic environment

Fish and eel passage

Due to the difference in water level across the weir, weirs can obstruct or delay fish migration, and the ability of fish to jump or swim upstream over a weir varies greatly with species and size. Weirs can also stop the recolonisation of a removed species, such as that of the white-clawed crayfish after a pollution event. Fish and eels are an important element of the biodiversity of rivers, and migration is a part of their natural lifecycle, so it is important to consider carefully their requirements during the construction or rehabilitation of any weir.

A weir should be designed to facilitate upstream migration if possible and to avoid causing harm to individuals during that migration process. The designer will need to consider a number of different technical and biological constraints and criteria, including the swimming abilities and behaviours of different species, river hydrology, hydraulic and hydromorphological design criteria, operational practice and other weir users. Where weir construction is proposed, mitigation features can range from close-to-nature bypass channels to technical fish pass solutions and the design decision process can be complex (see **Table 11.1**).

Where weirs are constructed or significantly altered, the law requires that, in certain circumstances, appropriate fish and eel passes are included in designs (see **Section 12.4.4**).

If a bypass channel or fish or eel pass is necessary, key issues to consider in design are location of the outlet at the furthest point upstream before the weir, maintaining sufficient attraction flow through the pass, gradient of the pass, provision of a suitable flow depth and velocity for the species and resting places (see **Section 13.8**). A by-wash for downstream migrating smolts may be required at abstraction points.

It is important to note that irrespective of design efficiency and effectiveness, all weirs with fish and eel passes can still delay, obstruct and hinder longitudinal migration. Any such delay has the potential to affect successful recruitment, which can lead to waterbody-scale population impacts as fewer individuals have sufficient energy to reach appropriate spawning habitats and reproduce, in comparison to a natural system. Putting a fish or eel pass on a structure does not mitigate all of the migration issues.

Heritage

As discussed in **Section 3.2.4**, weirs may be of historical significance, ie the actual weir, as part of a historic water management system or by contributing to the aesthetic setting or soundscape of a heritage asset. Weir management should have regard to the heritage and landscape value of a historically significant structure or waterbody, its setting and the associated recreational and commercial activities.

3.3.3 Geomorphology

Sediment continuity

In order to understand the geomorphological impacts of weirs on a river system, an understanding of the river type, river forms and processes is needed. The potential negative consequences of a weir scheme (over a range of spatial and temporal scales) should be identified during design and the scheme adapted to remove, reduce or minimise these impacts.

A weir can affect sediment continuity along a watercourse, with deposition of sediment within the impoundment zone upstream and sediment starvation in downstream reaches. This can lead to unwanted side effects such as reduced habitat diversity in the upstream reach and bed or bank erosion downstream of a weir. The nature and extent of the impacts depends on the type of river, size, location and orientation of the weir, type of weir and how long it has been present. Where sediment continuity is a consideration, perhaps for geomorphological or environmental reasons (eg to manage the quality of abstracted water or to prevent blockage of an abstraction point) the weir should be designed to manage sediment transport.

Scour and sedimentation

Flow conditions downstream of weirs are highly turbulent and will scour an erodible river bed until a weir pool of sufficient volume develops to dissipate energy released from the head drop at the weir. Deep weir pools and shoals downstream of weirs have environmental value, but can require scour protection and channel maintenance over time.

Excessive erosion can be avoided by incorporating a stilling basin downstream of the weir. Some of the energy released during the transition from supercritical to subcritical flow should be dissipated on the weir structure rather than conveyed downstream where it may undermine the structure or erode soft river-banks. The design should weigh up the cost of the weir structure, the risk to public safety, which can be posed by a highly effective stilling basin, and the cost of downstream bank protection. Depending on the channel geometry, hydraulic conditions and approach to the weir, scour protection may also be required upstream of the structure. Further information on scour and scour protection is given in **Section 13.7**.

3.3.4 Hydrology and hydraulics

In the UK, significant seasonal variation in flow can be expected and a weir should be designed to operate satisfactorily in all flow and water level conditions, eg normal flow, flood flow, extreme flow and low flow. A sound hydrological understanding of the river is required to estimate the likely range of flows and tailwater levels that a weir will be required to perform under.

In normal flow conditions, the desired range of upstream water levels will often be defined by functional objectives. A navigation weir may require limited variation in water level with flow to provide sufficient draught (and air draught beneath bridges). Land drainage may dictate that normal water levels are below the elevation of land drainage outfalls. Flow conditions at a gauging weir will usually need to remain modular for a given range of flows. An impounding weir for hydropower should not affect the tailrace of an upstream scheme.

During flood flows, a weir may need to have sufficient flow capacity to prevent out-of-bank flow for a given return period flood and to avoid impeding drainage to areas upstream. Where a new weir replaces an existing weir, matching the flow capacity of the new and old weirs at bankfull level will avoid increasing the frequency of out-of-bank flow. The risks posed by hydraulic conditions to land and water users, the weir structure and surrounding infrastructure should be acceptable.

If a weir is likely to be bypassed during extreme flows, constructing a channel around the weir will direct exceedance flows around the structure at a safe distance, thereby avoiding scour of the weir structure.

During low flows, any fish pass should be designed to ensure that attraction flow, drop height, velocity and turbulent energy limits and sufficient depth of water remain suitable for fish passage. The visual appearance of the weir may also be important. For example, a dry weir crest is less attractive than one conveying a small amount of flow.

The hydraulic performance of a weir depends largely on its geometry, ie plan form, crest length, level and shape, and configuration of the weir structure, as well as tailwater level.

3.3.5 Structural

Resist imposed loads

Weirs are subjected to onerous imposed loads that can vary significantly over their design life. Mobilising hydrostatic and hydrodynamic forces are greatest during low flow conditions when the weir retains a full head of water upstream, but the downstream water level may be low. Debris impact loads are most likely during flood conditions. Also, resisting forces can be reduced due to hydraulic action. Piping occurs when seepage flow beneath the weir has a sufficiently large hydraulic gradient on exit to cause boiling of the bed immediately downstream. This can lead to loss of soil and eventually undermining of the weir structure. Scour at the toe of the weir removes passive resistance and may undermine the weir structure. Uplift pressures on the base of a weir reduce resistance to sliding, while a low downstream water level reduces the weight acting downstream on a weir apron or stilling basin slab.

A weir should be designed to give acceptable hydraulic exit gradients, sufficient resistance to sliding, overturning and bearing capacity failure. Anticipated settlement should be within acceptable limits. Differential settlement is a particular concern for gated weirs as even small movements can prevent the operation of the gates.

Limit damage during extreme conditions

A weir should be capable of withstanding extreme conditions, both high and low flows. During high flow conditions, the location of the hydraulic jump influences the weight of water acting on a weir. If energy levels are high enough to sweep the jump to the downstream end of the stilling basin, the weight of water upstream of the hydraulic jump may be very low. However, out-of-bank flow is not usually the most onerous load case on a weir structure, although this may place excessive demand upon structures associated with the weir (such as approach embankments, wing walls or telemetry), particularly during post-flood drawdown.

The most onerous hydraulic loading upon a weir may well be during low flow conditions when water levels downstream of the weir are low and differential head across the structure is high. De-watering all or part of a weir structure (eg during maintenance, refurbishment or construction) reduces the weight of water on a weir substructure. This can lead to destabilising uplift forces, particularly if there is an existing piping issue.

Maintain a specified condition

Much of a weir is hidden from view and inaccessible, whether below water or ground. As a result, it must be remain durable despite little maintenance, whilst maintaining an acceptable visual appearance and sustainable use of materials.

3.4 INFORMATION GATHERING

One of the first stages in the development of a weir project is an appropriately scaled information gathering exercise. This may include a desk study of existing information, site walkover, surveys and ground investigation. Constraints and opportunities affecting the site should be identified. It is important to allow sufficient lead time for environmental baseline surveys as some can only be undertaken at certain times of the year, and consider the timings of different activities. For example, recreation may be seasonal or take place in the evenings or at the weekend rather than during the working day. Prompt lists for data gathering at different stages in a project are given in **Tables 3.3 to 3.5**.

Table 3.3 Prompt list for routine monitoring

Type	Description
Structural (**Chapter 8**)	Structural defects (eg cracking, surface defects, movement or leakage). Scour depth and extent.
Environmental (**Chapter 11**)	Water quality. Fish species, age and length class. Plant species.
Geomorphology and hydrology (**Chapters 12 and 13**)	Geomorphological monitoring. Flow monitoring.

Table 3.4 Prompt list for data gathering for objective-setting

Type	Description
Landownership and use	Land ownership (site and surrounding land). Historic and current land use (site and surrounding land).
Access	Access routes for initial investigations and construction, and constraints such as bridges with weight limits. Access by river if access by land is not possible.
Operation	Historical as-built drawings, operation and maintenance manuals, health and safety files. Historic data should be carefully checked and should not be assumed to be correct. Existing rating curves, operational practices and records, gate opening records. Operation and maintenance requirements that may affect choice of weir type (discuss with operational staff early on).
Navigation	Navigability of the river including expected boat movements, navigation or air draught and other requirements. Any restrictions that will affect works. Formal navigations are well documented, however navigation by unpowered craft on other rivers should also be considered.
Functions	The discharge for which out-of-bank flow occurs upstream of the weir and the discharge at which property begins to flood. Hydraulic constraints other than the weir. For example, upstream and downstream bridges may mean that the weir is not the hydraulic constraint on the channel for some flow conditions. An existing hydraulic model can be a useful starting point. Existing outfalls, intakes, land drainage and land use upstream of the site (to allow assessment of whether water level change and consequential groundwater level changes will be beneficial or detrimental).
Environmental (Chapter 11)	Designated and undesignated assets should be considered, following good practice relevant national planning policies (eg NPPF). Designated conservation sites and protected species. Fisheries information. Designated and undesignated heritage assets. Potential ground contamination or historic land use records. Consultation of local authority (LA) heritage professionals (archaeology and historic environment records (HER) officers).

Table 3.5 Prompt list for data gathering for design and implementation

Type	Description
Mapping	River valley upstream of site identifying critical infrastructure and gauging sites.
Survey	Dimensional survey of crest length and breadth, drawdown valves – presence, dimensions and operability, weir boards (to adjust crest height according to season). Topographic information extending sufficiently upstream to include likely backwater caused by weir. Longitudinal section of river bed and water levels. Bathymetric survey identifying bed material near the weir and significant features such as scour holes. Dive survey to understand the underwater construction and condition of an existing weir structure (see **Box 8.1**). LiDAR survey of floodplain for site compounds and access routes. Photographic survey of the site and reaches upstream and downstream for future decommissioning.
Searches	Risk of unexploded ordnance (UXOs) in areas likely to have been subjected to bombing or anti-aircraft fire during the Second World War (see **Box 3.2**). Services and utilities information. For powered weirs, all electricity supply details should be obtained and the capacity of existing power noted. If an additional power supply is likely to be necessary the location of the nearest substation should be confirmed.
Environment (**Section 6.3**, **Chapter 11**)	Environmental information for specific river reaches including surveys at a scale suitable for the proposed scheme. The adequacy of data held by Environment Agency, SEPA, Natural Resources Wales (NRW) and NIEA for the proposed scheme will need to be reviewed and the regulating LA should be consulted to define the need for additional data gathering.

Type	Description
Geomorphology (**Chapter 12**)	Historic observations and measurements of suspended silt, bed material and the development of geomorphological features. For large rivers, historical aerial photography as well as satellite imagery can be helpful. Current geomorphological survey and existing fluvial audit information.
Hydrology and hydraulics (**Chapter 13**)	Hydrometric data (stage and discharge). If discharge data is available at a distant downstream or upstream established gauging site over a number of years, the flows at the proposed site may be estimated by mapping to a shorter period of data at the project site. Consider installing gauges at an early stage of a project to give greater certainty later during the design period.
Geological and geotechnical (**Chapter 14**)	Geological maps. Exploratory hole logs and information from nearby schemes. Observation of surface soils, rock (where exposed), landforms and other site features including changes in vegetation, areas of poor drainage, evidence of instability, seepage and scour. Initial boreholes, soil samples, standard penetration tests (SPTs), concrete coring of existing structures should be considered. Annex B.3 of BS EN 1997-2:2007 recommends initial investigations for weirs to determine a vertical section, with holes at 25 m to 75 m spacing. This should be scaled to the structure under consideration – three holes might be considered the minimum requirement unless the structure is very small. For weirs and excavations below groundwater level, and where dewatering work is involved, the depth of investigation should also be selected as a function of the hydrogeological conditions. Additional, more closely spaced exploration holes with laboratory and in situ testing as design progresses. Destructive testing (eg rotary drilled coring) to provide information on weir construction, materials, foundation depth and load bearing material. Non-destructive testing (NDT) may determine foundation depth without causing any damage to the structure.

3.5 CONSULTATION

Stakeholders should be involved at an early stage of the project to ensure that their interests are taken into account. These include partners or primary stakeholders who are financially involved in the work, statutory consultants, advisory stakeholders and other interested parties such as community groups (**Table 3.6**).

Stakeholder engagement should be appropriately scaled and can take many forms, ranging from formal meetings with public and private bodies, to leaflet drops, notice boards and social media. The latter is highly effective in getting the message across to the wider public and allowing people to air their views (see **Case study A3.7**). Further guidance is available in Cabinet Office (2013), Collier (2011), Daly *et al* (2015) and Environment Agency (2006a).

Box 3.2 Unexploded ordnance (UXO)

Waterways (and weirs) are anecdotally at particular risk because ordnance landing in water is unlikely to have been recorded. Also, UXOs can be conveyed downstream to obstructions such as weirs.

Table 3.6 Typical stakeholders

Type	Stakeholders
Primary	Landowners or tenants
Statutory consultants	Planning authorities Organisations responsible for: ■ land drainage or flood risk management ■ water resources, nature conservation, fisheries and biodiversity ■ heritage
Advisory	Water and sewerage undertakers Navigation authorities Hydropower operators or promoters Catchment partnerships or rivers trusts Weir restoration groups or preservation trusts Sports bodies
Interested parties	Local: ■ sports clubs (eg angling, canoeing, rowing and other watersports) ■ interest groups (eg ornithology) ■ residents

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4 Is there a need to intervene?

4.1 INTRODUCTION

The need to intervene will depend on the existing performance of the weir, its condition and the rate of change, the legal and policy framework, and opportunities due to funding or other works nearby (**Table 4.1**).

Table 4.1 The need to intervene

Issue	Response
Does an existing weir perform well, have acceptable impacts and there are no opportunities to address?	If yes, no need to intervene
	If no, consider: ■ removal, part-removal, lowering or bypassing (**Section 5.3**) ■ refurbishment, repair or improvement (**Section 5.4**) ■ replace with an alternative (**Section 5.2**).

4.2 IMPACTS, BENEFITS, ISSUES AND OPPORTUNITIES

The impacts (positive and negative), issues and opportunities associated with an existing or proposed weir should be identified and a prompt list is given in **Table 4.2**.

Impacts can be short or long-term, temporary or permanent, and are dependent on numerous factors, including the river type, the location of the weir, the size of the weir structure, and other local controls influencing the river at the structure and surrounding area. Some impacts may require mitigation measures to avoid harm to the environment, while others may provide an opportunity to improve an area through environmental stewardship actions.

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Table 4.2 *Example issues and opportunities associated with interventions to weirs*

Aspect	**Removal, lowering or failure**		**New or replacement weirs**		**During physical works**	
	Issues	***Opportunities***	***Issues***	***Opportunities***	***Issues***	***Opportunities***
Safety (**Chapter 10**)	Temporary impact upon workers. Structural instability of river walls.	Reduce hazard due to deep water and recirculating flow.	Increased hazard due to deep water and recirculating flow.	Reduce safety hazards. Improve access for inspection and maintenance. Install drawdown facilities to decrease risks associated with maintenance. Create crossing point.	Temporary impact on workers and river traffic.	
Water quality (**Section 11.4**)	Temporary water pollution if contaminated or anoxic sediment mobilised.	Restore thermal and oxygenation regimes.	Reduced dissolved oxygen and increased temperature upstream of the weir.	Sympathetic weir design can reduce the impact on water quality downstream of the weir.	Temporary impact due to turbidity and contamination.	
Water supply or hydropower	Loss of flow measurement or impoundment for abstraction. Reduced income.	Use non-intrusive flow measurement or abstraction.	Reduced flows and depleted reaches. Unnatural hydrograph or flow variation. Debris accumulation. Increased maintenance costs. Habitat loss upstream Possible loss of amenity.	Abstraction for consumption or hydropower. Generate income.		Include provision for fish and eel passage.
Fisheries (**Section 11.5**)	Change in plant or fish species.	Improve fish and eel migration. Restore varied flow and habitat. Improve genetic diversity.	Delayed or obstructed fish or eel migration, reduced chance of reproductive success. Isolated and genetically impoverished populations. Habitat diversity loss, leading to impoverished populations and loss of angling amenity.		Temporary impact on migration and spawning habitats	
Aquatic and terrestrial ecology (**Section 11.6**)	Change in species and diversity. Invasive species migration upstream.	Restore riverine habitat and continuity of habitat. Create varied marginal habitat. Create habitats.	Silt smothering of habitat and reduced marginal vegetation upstream. Reduced habitat variability and biodiversity. Algal blooms. Invasive species colonisation of uniform habitat.	Excavate backwaters to create wetland habitat. Increased floodplain connectivity.	Temporary increase in turbidity due to disturbance of sediment. Temporary disturbance of nesting birds or protected species. Spawning habitat.	Mitigate (eg by providing additional nesting habitats). Timing of works.
Recreation and navigation (**Section 11.7**)	Reduced navigation draught. Changes to species and population distribution which may be perceived as detrimental by established angling syndicates	Improve public access and riverside recreation in more natural environment. Provide access for all. Increased diversity for angling. Increased income.	Barrier to navigation unless bypassed. Loss of some angling opportunities.	Improved navigation in impounded reach. Create white water feature for canoeists. Generate income.	Temporary loss of amenity (eg angling, navigation, canoeing).	Provide access for all, viewing areas, seating and picnic areas. Provide landing stages for boaters upstream and downstream.

Aspect	Removal, lowering or failure		New or replacement weirs		During physical works	
	Issues	*Opportunities*	*Issues*	*Opportunities*	*Issues*	*Opportunities*
Heritage and archaeology (**Section 11.8**)	Permanent and irreplaceable loss of built heritage (partial for lowering, complete for removal). Harm to significance of designed landscapes or historical complexes.	Preserve mill race as open water (at lower level).	Permanent damage to existing weirs and underwater archaeological material by local scour or bank erosion.	Provide heritage interpretation boards	Permanent disturbance of submerged or buried historical fabric.	Desk-based assessment of significance of elements and whole. Staged scheme of archaeological investigation and recording Install heritage interpretation boards.
Landscape and visual impact (**Section 11.9**)	Loss of designed landscape. Loss of visually present impounded water.	Regeneration of natural riverside and flowing water. Create alternative features. Reduce noise.	Loss of natural landscape. Increased noise due to water.	Create designed landscape. Create permanent waterfront. Regenerate riverside.	Noise during works.	Provide construction information boards. Use local building materials.
Geomorphology (**Chapter 12**) Many responses to removal, failure or lowering only become issues when they exceed a threshold that deem them to be an uncontrolled response.	Increased stream power. Sediment mobilisation upstream and deposition downstream. Knick-point recession. Bank erosion or undermining, exposure of buried utilities.	Restore natural geomorphological processes (vertical and lateral). Improve sediment transport and morphological diversity.	Interrupt sediment transport. Sediment deposition upstream reducing habitat diversity. Sediment starvation, scour and structure undermining downstream. Simplification of processes and loss of habitat diversity.	Locate weir to reduce impoundment length and risk of outflanking. Design to maintain sediment transport. Minimise impacts on channel geometry. Design to minimise impact of future failure or removal.	Fine sediment mobilisation to downstream reaches unless mitigated. Risk of damage to existing river bed and banks unless mitigated.	**Construction:** improve geo-morphological condition within zone of impact (eg place large wood to provide diversity in impounded zone). **Demolition:** mitigate some of potential response (eg plant river-banks to provide stability).
Hydraulics (**Chapter 13**)	Reduced water level upstream, with possible impacts on groundwater. Change in stage and frequency of out-of-bank events. Impact on gauging records. Steeper hydraulic gradient and potential for erosion, scour and damage to structures and services.	Remove impoundment zone upstream. Increase bankfull flow capacity upstream.	Reduced flow velocities upstream. Changes in flow regime downstream of the weir. Impact on gauging records.	Reduced hydraulic gradient and potential for reduced erosion and scour.	Temporary change in water or groundwater level upstream. Temporary change in hydraulic gradient and erosion potential.	–
Land drainage and flooding (**Chapter 13**)	Reduced floodplain connection. Change in local flood risk.	Increased groundwater storage capacity at times of heavy rainfall.	Increased water level and flood risk upstream. Change in floodplain wetting frequency. Impact on land value.	Ability to measure flow accurately. Improved operation.	Temporary change in flood risk.	–
	Improved land drainage upstream (may be beneficial or detrimental depending on local environment).		Higher groundwater levels in the reach upstream (may be beneficial or detrimental depending on local environment).			

4.3 REFERENCES

BARLOW, J, MOORE, F and BURGESS-GAMBLE, L (2014) *Working with natural processes to reduce flood risk*, R&D framework: science report, SC130004/R2, Flow and Coastal Erosion Risk Management Research and Development Programme, Environment Agency, Bristol, UK (ISBN: 978-1-84911-331-1)
http://evidence.environment-agency.gov.uk/FCERM/Libraries/FCERM_Project_Documents/WWNP_framework.sflb.ashx

ECRR (2014) *Managing water for flood risk and the Water framework Directive*, European Centre for River Restoration
www.ecrr.org/RiverRestoration/Floodrisk management/HealthyCatchmentsmanaging forfloodriskWFD/tabid/3098/Default.aspx

5 What are the options?

5.1 INTRODUCTION

Options for existing weir structures fall under removal, lowering, refurbishment, repair, improvement or replacement (or allowing it to fail). A new weir may be considered in some cases. A weir structure may not be required at all and, if this is the case, consideration should also be given to alternatives that can give desired outcomes without the need for the weir structure (**Figure 5.1**). Feasible options will be guided by legal requirements, engineering, environmental and geomorphological constraints, heritage and other factors involved in the management of the structure, in particular the WFD (see **Chapter 8**).

5.2 TYPES OF WEIRS AND ALTERNATIVES

Two types of weir can be defined – fixed crest (**Section 5.2.1**) and movable (**Section 5.2.2**). Movable weirs are typically used where greater control over upstream water level is required, or where there are other requirements such as river navigation or sediment management. The stage-discharge relationships for these two categories are shown in **Figure 5.2**.

The overall footprint of a gated weir structure can be smaller as a higher flow can be passed by opening the gates. Providing gates in a weir can also allow the passage of sediment and trash, which reduces the tendency for these to accumulate behind the weir. These benefits should be balanced against the higher operational legacy of a movable weir, both in terms of maintenance of moving parts and the usual requirement to actively operate the structure to pass the design flow. For this reason, gated weirs often have a fixed weir located alongside, in order to limit the daily operation of the gates.

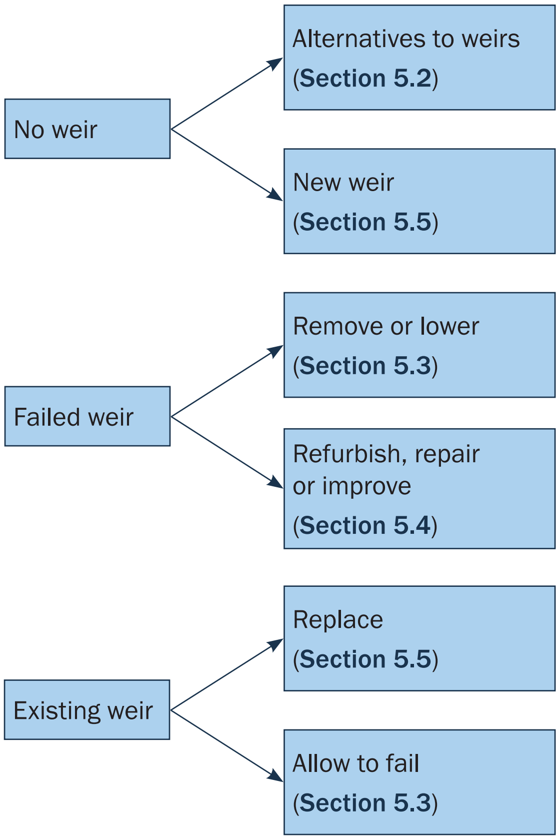


Figure 5.1 Options for weirs

5.2.1 Fixed crest weirs

Under normal flow conditions, fixed crest weirs have a singular stage discharge relationship that is defined by their geometry. To achieve the required discharge curve, the crest length of the weir can be increased within the available space in the river and the crest shape can be altered to increase the efficiency of discharge. A large variety of plan and sectional geometries are available to suit different purposes (see **Tables 5.1 and 5.2**). A more detailed reference sheet for each weir type is included in **Appendix A1.1**.

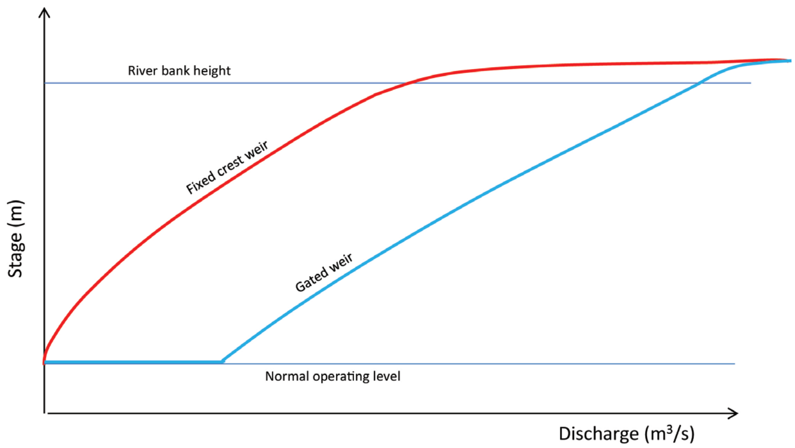


Figure 5.2 ***Stage discharge curves for fixed crest and gated weirs***

Table 5.1 ***Fixed crest weir arrangements***

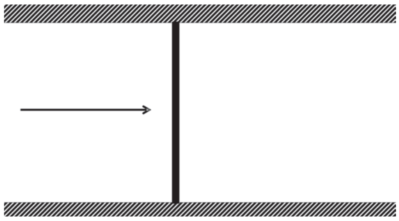
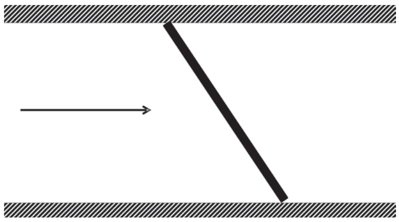
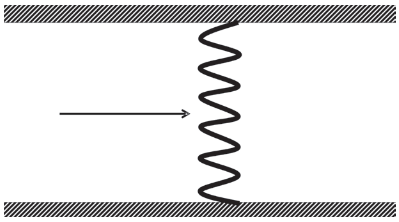
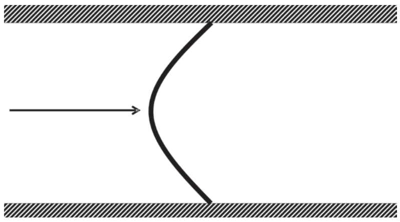
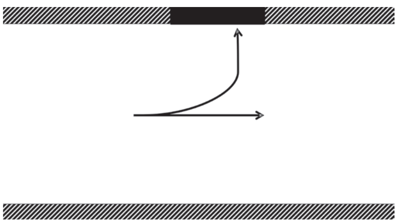
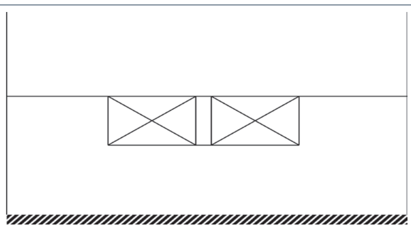
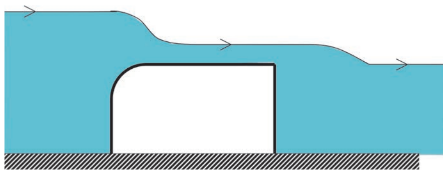
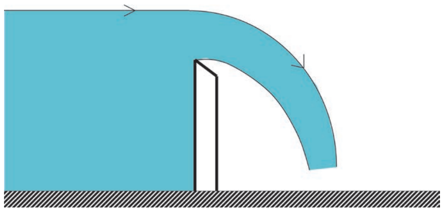
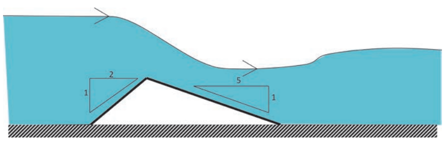
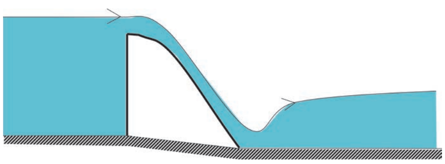
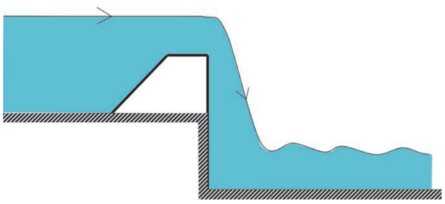
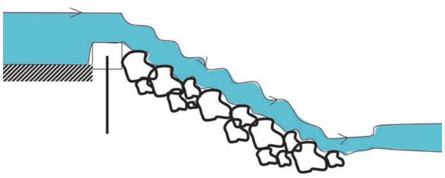
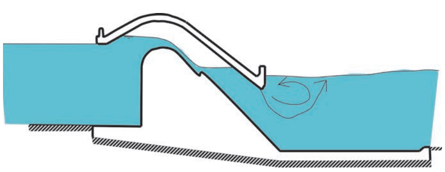
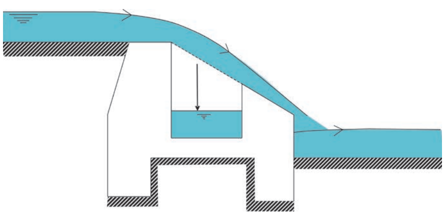
	An **orthogonal** arrangement spans the river at a right angle to the flow direction. This is the most commonly used weir alignment due to simple approach hydraulics, minimal use of material and ease of design.
	A **diagonal** arrangement spans the channel at an angle to the flow to increase the crest length, thereby increasing the discharge capacity of the weir. The enhancement to discharge capacity is less pronounced for higher flows, where the weir begins to behave similarly to the equivalent orthogonal weir. Diagonal weirs can create more complex approach and downstream hydraulic conditions and make for difficult stilling basin design.
	A **labyrinth weir** is a linear weir that is corrugated in plan-view to increase the crest length and discharge capacity of the weir. The enhancement to discharge capacity is less pronounced for higher flows, where the weir begins to behave similarly to the equivalent orthogonal weir.
	The **curved** alignment of the weir acts to increase the crest length, raising the discharge capacity of the weir. At very high flows, the weir will behave similarly to an orthogonal weir of the same type. These types of weirs often have high visual appeal.
	**Side weirs** are used widely to divert flows from rivers, canals, sewers and reservoirs. However, their hydraulic behaviour is complex and difficult to predict accurately by simple methods.
	**Gated weirs** often have a fixed weir located alongside to limit the daily operation of the gates. Weir complexes comprise one or more different weirs across a watercourse, acting in parallel to control upstream water levels and convey flow downstream.

Table 5.2 Fixed crest weir sections

	**Broad-crested weir** structures can have control sections of a variety of shapes including triangular, parabolic, trapezoidal and circular. The use of a broad-crested weir for flow measurement is dependent on the weir crest height above the channel bed being sufficient to generate critical depth at a control section on the crest. Most weirs in rivers can be approximated to broad-crested weirs although their structure and form can vary significantly.
	A **sharp-crested weir** (or thin plate weir) is an overflow structure where the length of crest in the direction of flow is extremely short, typically of the order of two millimetres or less. Sharp crested weirs are often used in laboratories, or as temporary gauging structures in small streams and in sediment-free water
	**Crump weirs** are of standard geometry used for gauging flow. These structures have inclined upstream and downstream faces with an intersection at a horizontal crest line across the channel. The standard gradients for the structure are 1:2 on the upstream face and 1:5 on the downstream face. This can have benefits for sediment transport.
	The shape of the weir crest for **ogee weirs** is curved to match the profile of the water surface under the nappe of water flowing over the structure. This is generally recognised as being the ideal weir profile shape for the conveyance of flood water and is commonly used in reservoir spillway design.
	**Straight drop weirs** consist of a sharp drop after a weir crest, usually directly into a stilling basin. The steep downstream face of the weir results in plunging flow and has a tendency to create dangerous recirculation in the stilling basin. These types of weirs can be a significant safety hazard and are no longer seen as good practice. Existing weirs of this type can usually be altered to improve hydraulic safety.
	**Rock weirs** and rock ramps are formed from dumped rock sized to withstand the flow conditions at the weir site. They may be used to create adequate head for diversion/abstraction, to maintain fish passage during low flows and to regulate channel gradient for erosion control. A rock ramp is usually provided with a low-flow channel designed to give suitable conditions for fish passage during low-flow conditions.
	A rarely employed alternative is the **air-regulated siphon**. These structures are self-regulating with no moving parts and are able to achieve large discharges for small increases in upstream water level. Although there are some examples in the UK, these structures have rarely been constructed in the past, partly because of historic concerns around trash and ice blockages and lack of design precedents.
	**Tyrolean and Coanda screen weirs** are used for in-channel intakes on steep streams. A flat or inclined rack of bars is placed on the downstream face of the weir, to allow water to drop into an off-taking channel within the weir body. Trash and coarse sediment is excluded by the bars.

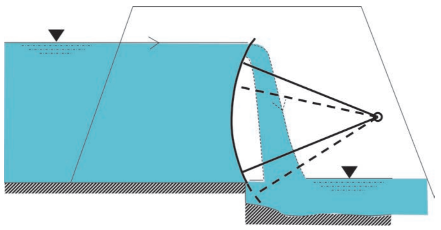
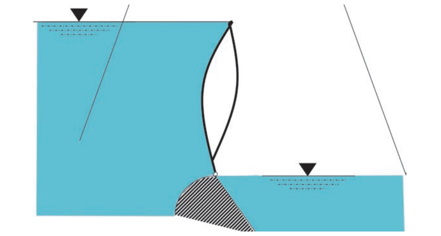
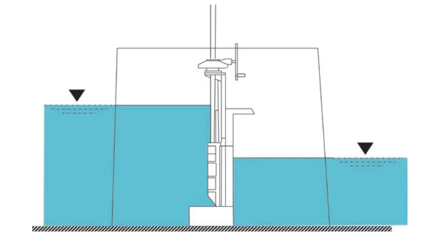
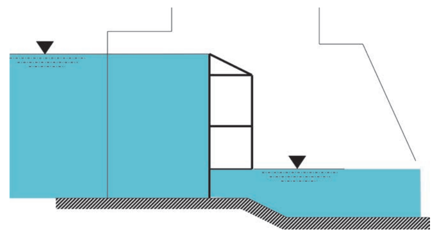
5.2.2 Movable weirs

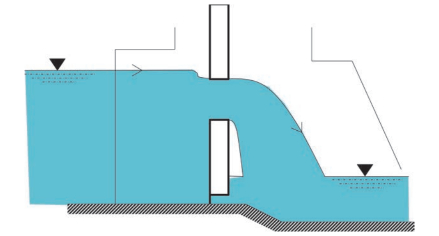
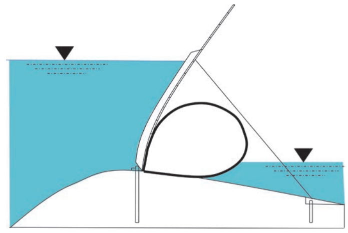
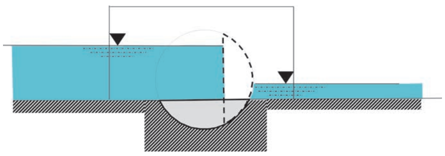
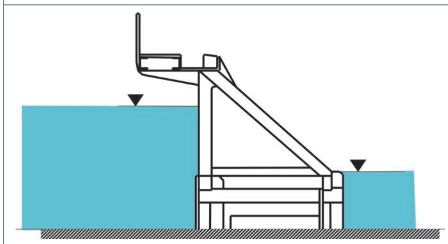
Where a fixed crest weir cannot provide adequate flow capacity, water level control, or where there are other requirements such as river navigation, sediment management, or a need to regulate water levels during turbine start-up and shut-down, it is usual to provide a movable weir.

Although there are still notable examples of manually operated movable weirs, this type of operation is now usually avoided for structures of a reasonable size. This is because of slow operation and the requirement for manual handling, which can cause health problems for staff operating the weir. For most modern structures of reasonable size, mechanical, electrical, instrumentation, controls, automation (MEICA) equipment is provided to enable safe and controlled regulation. Most commonly steel gates are used and these are moved using hydraulic rams, electric motors or valve actuators with gearboxes and hoists. However, a large variety of different types of gate and systems for gate operation have been designed in the past. At sites without power or unattended sites, gates can be designed to operate automatically in response to upstream and downstream water levels (usually gates are counterweighted and operated gradually either through buoyancy or weight of water).

Selecting a gated weir type for a new structure depends on several competing considerations including weir function, cost, operation and maintenance, civil to mechanical interface, failure mode (open/closed) and visual impact of the structure. A summary list of the different types of movable weirs typically used in the UK is given in **Table 5.3**. A table comparing their relative merits against key criteria and a more detailed reference sheet for each gate type is included in **Appendix A1.2**.

Table 5.3 List of commonly used gated weir types

	**Radial gates** (also known as segment or Tainter gates) consist of a segment-shaped skin-plate arranged over a supporting structure with radial arms to pass the hydraulic forces to bearings located either side of the gate. Where fine water level control is required, dipping radial gates or top-flaps may be used to allow more controlled discharge and the passage of ice and trash.
	**Bottom-hinged flap gates** consist of a straight or curved-shaped gate structure hinged at the base of the gate. They can be designed sufficiently stiff in torsion so that they can be moved using a hydraulic actuator from one side only. This may be particularly beneficial where visual impact is of concern, as the actuating equipment may be largely hidden within one of the weir piers.
	Due to their simplicity of design, construction, operation and maintenance, **small sliding penstock gates** are commonly found on UK weirs and sluices. The gates may be made of a variety of materials including timber, steel, high-density polyethylene (HDPE) and cast iron.
	**Vertical lift gates** (also known as buck gates in the UK) are the most commonly used gate for flood control in river and tidal structures. The gates are simple in design and operation. They can be operated under unbalanced head conditions and lifted clear of the water for maintenance.

	A **split leaf vertical lift gate** is divided into two or more independently actuated sections. Fine water level control and trash passage is achieved by raising the upper section. Similarly, the vertical lift (hook type) gate is divided into two linked sections, arranged so that the upper section can be lowered for fine flow control and trash clearance.
	**Inflatable rubber weirs** are beginning to be used in the UK to retain a level of water in flood relief channels during low flows for environmental and aesthetic reasons (weir inflated), while maintaining the full capacity of the channel for flood flow (weir deflated).
	'**Sector gate**' is more commonly used to describe conventionally actuated segment gates that are housed in the open position within a recess in the weir sill. Sector gates are typically employed for tidal barriers where an unobstructed channel is required for navigation, such as at the Thames Barrier.
	There are a number of historic **timber weir systems** still in operation in the UK and Europe. The systems vary, but are based around the manual insertion of timber apparatus into the river. Their use is now widely being phased out due to concerns around the level of manual handling required for operation. However some examples remain to preserve the heritage value of this type of operation.

5.2.3 Alternatives to weirs

More natural methods of water level management, flow measurement or abstraction can perform the functions of weirs while avoiding or reducing the geomorphological, environmental and safety impacts. The alternatives available depend on the objectives, catchment process and river type. Alternatives to weirs are given in **Table 5.4** and river typology is given in **Table 12.1**.

Table 5.4 Alternatives to weirs

Example	Description
Water level management with natural obstructions emulate the natural river channel. The choice of method should suit natural processes of the catchment and river type and measures are best designed by an expert geomorphologist (see **Sections 3.2.1 and Section 12.4**).	
	**Rock ramps** use rip-rap to create a steep, immobile reach that creates sufficient water depth, maintains fish passage and controls discharge capacity. These can reduce obstruction to fish passage and improve sediment continuity. See **Case studies A3.11 and A3.12**.
	**Modify channel width** to narrow, widen or create a two-stage channel along a reach or at specific points. This can improve floodplain connectivity or increase water depth for abstraction. Avoids impounding structure that obstructs fish passage and sediment transport.
	**Morphological features** such as riffles, pools, rapids, runs, bars, berms, boulder clusters and large wood can be introduced either singly or in series to improve geomorphology, habitat and the environment. Material should be suitably sized to avoid complete washout of features, and designed and placed carefully to avoid significant impoundment or obstructing fish passage.
	**Lowering the river-bank or floodplain** allows more water onto the floodplain at higher flows (eg as part of a flood storage scheme or wetland creation). This can be employed alongside other techniques.
Natural flood management (NFM) improves connectivity between a river and its floodplain where this does not affect people, property or valuable land. This can avoid the need for a weir to raise upstream water levels and divert water from the river to the floodplain. NFM is often used to reduce the severity of smaller, more frequent flood events rather than eliminate flood risk associated with more extreme events. See **Section 3.2.1**, Barlow *et al* (2014) and ECRR (2014)	
	**Increase infiltration** (eg by afforestation). **Store water:** reconnect river and floodplain (eg by bank lowering), install large wood features, restore or create wetlands, or install floodplain features to store or slow water. **Slow water:** slow down overland flow to increase the time it takes to reach river channels, restore the morphology of channel bed, re-meandering and pools.
Non-intrusive flow measurement can be installed on open channels, but has limitations in accuracy compared with weirs that have a unique stage-discharge relationship, allowing calculation of discharge from a simple measurement of flow depth over the weir crest. Research and development is ongoing to overcome some of the functional drawbacks. Further information is given in **Section 3.2.2**, and in RRC (2013) and SEPA (2013).	
	**Direct measurement** of flow uses an acoustic doppler velocity flow meter, time-of-flight ultrasonic flow meter or electromagnetic gauge. Some methods can be susceptible to weed growth, mobile bed and suspended sediment.

Example	Description
	**Indirect measurement** of flow area and velocity uses a current meter, acoustic doppler or dilution gauging. This requires a straight, stable channel, where stage is suitably sensitive to discharge, unaffected by weed growth or variable backwater conditions.
	**Flumes** measure critical flow depth at a local contraction, either manually or automatically. This provides a relatively robust, clear passage for water with small afflux. Flumes are suited to small watercourses, and often used in water and waste water treatment, irrigation systems and as throttles for flood storage reservoirs.
Non-intrusive abstraction can reduce impacts on geomorphological processes and diversity as long as designed features are aligned to processes of the river type. Abstraction of water can have a detrimental effect on geomorphological processes, both locally and downstream, and lead to entrapment of fish, sediment deposition and direct loss of riparian habitat (see **Section 3.2.5** and SEPA, 2008).	
	**Bankside, river bed or submerged intakes** can be installed in the river-bank (with or without a flow deflection structure), across full width of river bed or below normal water level. **Modification of channel width** creates a local reduction in channel width to increase water level and flow depth. **Morphological features** (eg riffles and pools) to create deeper zones of water.

5.3 REMOVAL, LOWERING OR FAILURE

Weir removal or lowering of obsolete structures is potentially cheaper than repair or replacement and reduces long-term inspection and maintenance costs. These options are increasingly in favour to removing barriers to fish migration and improving the geomorphological condition of all rivers in the UK to a 'Good' status helping to meet WFD objectives. Removal provides an opportunity to restore fish passage fully – fish passage can be delayed or impaired, even with a fish pass.

In the absence of other drivers, weir removal or modification should be considered as a preferred option when considering alterations, maintenance or other management decisions associated with the structure. This is because the environmental, ecological and geomorphological gains will help waterbodies reach WFD status objectives.

It is not always possible to remove or modify a weir structure. Reasons for this can include:

- difficult access
- historical or heritage value
- response of the river to the removal (eg increased instability upstream)
- requirement to maintain a navigable depth upstream of the structure
- flow gauging weirs or structures that have a significant record length or strategic purpose
- other river uses upstream such as abstraction.

Alternative measures such as lowering or partial removal can be considered to help improve the condition of the waterbody (see **Section 5.3.2**).

5.3.1 Weir failure

Weirs can fail naturally through foundation undermining due to water seepage beneath the weir or erosion downstream. In addition, outflanking of the abutments, material deterioration due to physical or chemical processes, improper operation or environmental loading outside of the designed capacity of the structure can lead to failure. These can have further impacts on river processes and action may be required to avoid flooding or pollution due to uncontrolled release of sediment (which may be contaminated), and to safeguard further structures upstream and downstream, requiring potentially large financial expenditure. Controlled weir removal or lowering is usually preferable to allowing a weir to fail unless the weir has been designed or sited to fail. Weirs that are

located within bedrock reaches will minimise the impoundment length and geomorphological impact and provide a stable foundation for siting the weir. Locating a weir below a natural 'step' (eg steep gradient bedrock reaches), fall or cascade in the channel can reduce the impacts on sediment transport and conveyance, and consequently any response post-removal or decommissioning, or failure of the weir.

The potential impacts on river processes associated with uncontrolled weir removal are summarised in **Table 4.2 and Section 12.2**. Inspection is covered in **Section 8.2**. See also **Box 5.1 and Case studies A3.2 and 3.3**.

5.3.2 Weir removal

Weirs are removed because they no longer serve a purpose and it is expensive to maintain them. Removal is generally seen as a beneficial for health and safety, fish passage, geomorphological condition and processes, habitat quality, availability and connectivity and natural river processes. It is also identified as a mitigation measure in the river basin management plans (RBMP) developed for England and Wales to improve the ecological status of waterbodies to allow them to achieve status objectives. Many weir removal schemes have been delivered across the UK, particularly in the last five to ten years. The benefits of weir removal are summarised in **Table 4.2 and Chapter 12**. See also **Box 5.2 and Case studies A3.1 to A3.8**.

A river's response to weir removal is strongly dependent on local conditions and variables and assessments for impacts of weir removal should be undertaken by an experienced geomorphologist, although minimal input may be needed for small weirs or low-risk sites. This assessment approach can take various forms such as a fluvial audit, hydraulic or sediment modelling and monitoring (see **Section 12.3**). The importance of the assessment approach is to ensure the geomorphological response of the watercourse to removal is fully understood to ensure this is acceptable, particularly in the reaches upstream where there could be an increase in river energy levels. The assessment should also consider responses up and downstream of the weir and change over a range of temporal scales. This is because the river will continue to react to the removal of the weir over time and at different rates depending on the river type and associated activity levels.

The impacts associated with weir removal should be predicted as part of an expert geomorphological assessment and measures put in place to address potential consequences and to provide some stability post-removal where this is required. In many cases, these responses occur in

Box 5.1 Rawstenstall weir failure

The weir was a significant barrier to fish passage at around two metres high. The structure was in poor condition and there was a known risk of failure. Work was not undertaken and the weir failed during high flow conditions, revealing a timber framework beneath stone pitching. There is a highly active section of watercourse upstream and the response has been significant with erosion of both river-banks, bar formation and cutting of chute channels through this bar and another further upstream.

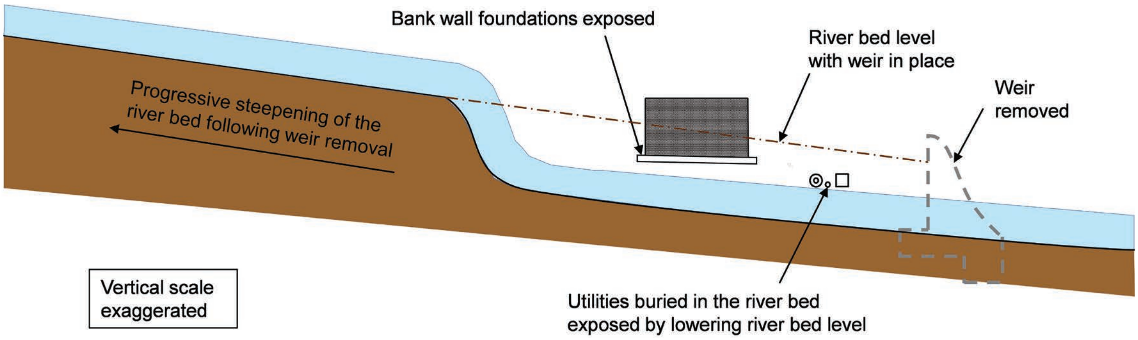


Figure 5.3 Potential effects of weir removal

Box 5.2 Weir removal at the River Lambourn, Woodspeen, Berkshire

This weir was removed at Woodspeen in Berkshire to eliminate the impounding influence upstream of the structure that was causing significant sedimentation issues. An upstream off-take sluice was also lowered to allow its continued function (see Elbourne *et al*, 2013).

the short-term or immediately following removal of the weir structure, and in the long-term they often stabilise. In addition, often any remaining consequences of weir removal are outweighed by the wider benefits gained. An expert should have a good understanding of the river type and its energy levels in order to assess the potential response to weir removal (see **Section 12.3**).

When considering the removal of a weir, particularly in an urban environment, it is important to understand the behaviour of the newly-steepened channel and to quantify the potential damage (or cost to mitigate damage) to the existing structures around the river. Remedial works might need to extend some way upstream and include, for example, lowering or protection of buried services, strengthening and deepening of bank walls and protection of bridge piers and abutments (**Figure 5.3**).

5.3.3 Weir lowering, partial removal or breaching

Weir lowering, partial removal or breaching can be viable where risks associated with full removal are high, to maintain acceptable stability upstream of the weir, but to also maximise improvements in natural geomorphological processes (ie partial removal of the impoundment to allow some recovery in the natural flow and sediment regime upstream). This may be undertaken alongside fish passage construction where the lowering does not satisfy fish passage requirements. Weir lowering is likely to moderately increase the water surface gradient upstream to allow some sediment transport to take place and improve geomorphological condition of the channel upstream. Where feasible, weir lowering or partial removal can be undertaken as an adaptive approach towards full removal of the weir structure. This will help to understand how the river will respond upstream and allow decisions to be made as to whether full weir removal is possible.

Partial removal or breaching can involve removing a certain portion of the weir laterally (rather than vertically as for weir lowering) to maintain channel stability over one side of the channel, perhaps where critical infrastructure is located (see **Figure 5.4, Box 5.4 and Case study A3.3**).

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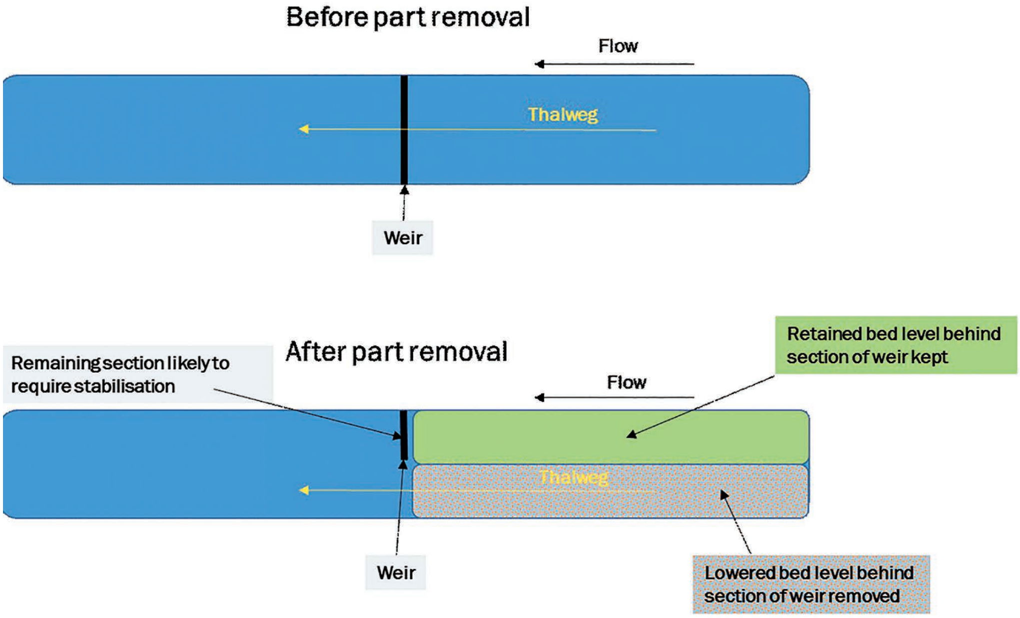

Figure 5.4 Example of partial removal

Box 5.3 *Part removal of a weir, River Colne, Essex (courtesy Andy Pepper, ATPEC River Engineering Consultancy)*

The partial lateral removal of the weir from the River Colne, lowered water levels upstream, allowing a more natural river channel and diverse habitat to develop within one year. The increased risk of erosion resulting from flow constriction, turbulence and velocity was controlled by the brick wing walls, which were retained.

Box 5.4 *Multi-use, multi-benefit bypass channel at Radcot lock*

Built in 2011 as part of the weir replacement scheme at Radcot lock, the fish and canoe pass is a semi-natural bypass channel that uses manufactured brushes to help lower the water velocity at key points along the pass. After completion it was an unattractive, bare and muddy channel. In 2013 a fish survey was carried out to assess the use of the pass by fish. Not only had the fish pass matured into a very natural looking channel, there were also high numbers of fish present. Over 170 fish were caught (with many missed by the team in the fast flowing water) with 11 species represented including several brown trout.

5.3.4 Weir infilling

Where weir removal or lowering is not possible, river continuity and fish passage improvements can be gained through infilling across and downstream of the weir using suitable bed material. This removes the 'step' created by the presence of the weir and gradually reduces the head difference through design of a suitable slope for the bed infilling. This could involve creation of a rock ramp (see **Case studies A3.11 and A3.12**). It could also be achieved by using a series of features, such as boulder steps, which create a step-pool type system across where the weir existed removing the obstacle to fish passage, but does not require removal or modification to the actual weir structure.

5.3.5 Weir bypassing

Where no modification to a weir structure is possible because of the heritage value associated with the structure, creating a bypass channel around the weir is another option to improve ecological condition. However, this is unlikely to improve geomorphology if the impounded level is maintained (see **Boxes 5.5 and 5.6**). The nature, length, slope and geometry will be dependent on local conditions to the weir and also controlled by surrounding land use. Bypass channels often involve the creation of a series of grade control structures that may appear as a series of boulder steps with pools in between. Some flow may be retained over the weir structure and the rest through the bypass channel. In areas where there is a high risk of poaching, bypass channels may need to be constructed from materials that discourage poaching or fenced off to prevent poaching.

5.4 REFURBISHMENT, REPAIR OR IMPROVEMENT

In order to withstand the changeable environment of a river, weir structures have to be robustly designed. This means that the useful life of a weir foundation will usually exceed that of operational equipment installed upon the weir. Extension to the serviceable life of a weir structure can often be gained by rehabilitation and repair, with some weir structures seeing multiple refurbishments over their lifetime before being decommissioned.

As well as rejuvenation of aging assets, a significant number of weir improvement projects have occurred over recent years because of requirements to improve fish migration and riverine habitat under the WFD. Other projects have resulted from the need to meet modern design standards, modern standards of flood protection and to improve operational and hydraulic safety. The presence of an existing weir structure can also make retrofitting of small hydropower financially viable where a new-build project may not be.

Box 5.5 Bypass channel, River Chelt, Cheltenham, Essex

The weir on the River Chelt at Cheltenham was identified as providing a barrier to fish and creating degraded geomorphological conditions upstream. A fluvial audit and hydraulic modelling was undertaken to determine a suitable option for the weir. Weir removal was not an option due to historical value and so options for bypassing the weir were explored.

A bypass channel was subsequently designed, using hydraulic modelling and recreating analogue features identified during the audit to define a dynamically stable meandering plan form with suitable morphology.

Bypassed weir

Bypass channel point bar

Box 5.6 *History of the weir at Radcot, River Thames, Oxfordshire*

In 1794 (engraving dated 1810) the weir was at a different site and described as: *"rude railing stretches across the stream from a group of willows on one side, to a bank with two thatched habitations on the other"* (Thacker, 1920). The old paddle and rymer weir at the current site dated from 1892 and was part-refurbished in 1993. The weir was replaced with a modern radial gated structure between 2010 and 2012, however the operation of other similar historical weirs were preserved as examples.

As a result, rehabilitation, repair and improvement projects are significantly more common than new-build or replacement schemes and it is important to understand the unique challenges, risks and opportunities that these projects present.

5.4.1 Understanding the structure

The type, function and particular operational nuances of an existing weir will usually be well understood from its recent history of operation. However, weir rehabilitation projects are often seen as relatively high-risk construction projects due to the combined requirements of working in the river and because they typically involve reliance on an old (and often poorly understood) structure.

Understanding the nature of old structures can be difficult due to the absence of original drawings and because unrecorded alterations to the design may have taken place during or following the original construction period. A significant effort to understand the history of the structure can be required particularly as construction spanning several generations may have occurred at the same site, with past repair and rehabilitation projects often incorporating parts of the old structure. Historic drawings and construction photographs can provide some insight into the make-up of a structure, as can experience of similar structures in the area (**Box 5.7**).

Old weirs often have heritage or archaeological value, and can be located directly over or close to ancient river crossings or on the same site as

a previous weir. Refurbishment or alteration of existing weir structures should consider the presence of archaeologically valuable structures, which may require preservation as part of the new structure (see Barker *et al*, 2007). In urban areas a weir can have significant value in providing a highly visible and often attractive context to industrial processes and heritage. Rehabilitation projects should be sensitive to this and where possible preserve and enhance elements of a weir that are historically valuable.

5.4.2 Identifying the issues

Some of the more commonly encountered issues for repair, rehabilitation and improvement projects are:

- **Repairs** make good damage to the weir structure that may have occurred over time (eg infilling of scour holes or concrete repair).
- **Rehabilitation** is a more fundamental intervention to rejuvenate elements of the weir, typically back to their original design standard (eg overhaul of hydraulic steelwork or sheet-piling works to protect the structure).
- **Improvement** enhances the ability of the weir to deal with contemporary requirements (eg inclusion of fish passage, improved safety features or operational practices).

Defining repairs and rehabilitation measures can be difficult as deterioration of the weir structure may have occurred which may not be immediately apparent due to being hidden underground or underwater. The first step is to try to understand the current condition of the structure. Dive inspections, bathymetric surveys and intrusive surveys are often required to assess the existing structure, however, even if these are carried out a degree of uncertainty will always remain. Commonly, structural issues are only properly understood after a contractor has mobilised and temporary works are installed to allow dewatering of the weir. Sometimes only when demolition or alteration of the weir structure has started can a clear picture of the existing structure be determined. Investigations, design of rehabilitation works and contractual provisions may need to take into account uncertainty around the existing weir structure.

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Box 5.7 *Retrofitting a fish pass and an eel pass to Belmesthorpe flow gauging weir, Rutland*

Eel pass ready to be installed on weir side wall

Fish baffles partially installed across downstream glacis

Fixing baffles at glacis toe

Completed retrofit

A weir rehabilitation project should not only address the material repair and rehabilitation of a weir. The opportunity should also be taken to examine and update:

- operation and maintenance procedures
- public and operational safety provisions
- where applicable, communication protocols and emergency preparedness and flood risk management procedures
- geomorphological and ecological function and aesthetics.

5.4.3 Scour

Large weir pools are a common sight downstream of old weirs and they occur when the natural bed has eroded. This is not a problem – in many cases deep weir pools are an attractive and valuable habitat for some fish and plant species as well as being aesthetically pleasing to people. However, excessive scour can begin to threaten surrounding land and the weir structure. This can indicate inadequate stilling provision, insufficient or non-replenished scour protection or poor operational practice. Rehabilitation work might include measures to replenish scour protection and/or improve the efficiency of hydraulic energy dissipation. The latter should be balanced against the value of the weir pool habitat, the hydraulic safety of more aggressive stilling and perhaps the cost of constructing a stilling basin over a very deep weir pool.

Old weirs can comprise a variety of materials. It is common to find composite structures made from materials including timber king-piles, timber beams, timber shuttering, concrete of varying strength, masonry, cast iron, reinforced concrete and ballast fill. Timber kept in anaerobic conditions can survive for a long time, however, the abrasive and highly oxygenated environment of a weir pool often means that old timber sheeting and piles that have been in the water for a long time can be decayed. This is a particular issue where timber sheeting retaining the weir foundation is no longer present and a scour hole has extended underneath the weir apron. This situation can be aggravated by the burrowing of signal crayfish and can be a serious threat to the structural stability of a weir.

Further guidance on hydraulic energy dissipation can be found in **Section 13.6**. Further guidance on scour and scour protection can be found in **Section 13.7**.

5.4.4 Subsurface conditions

Deterioration of conditions underneath a weir founded on permeable material can result from the washout of fine material due to seepage. Evidence that this is occurring can be difficult to obtain, but might include indications of voiding under the structure and downstream scour protection from probing surveys carried out by divers. In the extreme, cracking and movement of the weir structure might be evident. Washout due to seepage around the sides of the weir might result in sinkholes in the abutments. Major weir structures tend to be fitted with piezometric instruments, which can indicate abnormal pressure distributions under the structure. However, these are relatively rare in the UK, due to the nature and size of the structures under consideration. Any indication of material washout underneath the weir should be examined carefully as it could have ramifications for the overall safety of the structure. Progressive piping failures accelerate with time, so recognising the issue early is vital. Further information around design against piping can be found in **Sections 7.2 and 14.3.5**.

5.4.5 Deterioration of structural works

The river environment can be harsh and inhospitable to the materials that make up a weir. Masonry, brick and concrete structures can be affected by freeze–thaw expansion and contraction, efflorescence, thermal expansion and contraction, corrosion of embedded metal parts, failure of pointing, water and sediment erosion, plant growth, structural movement and the effects of birds and other animals. Vandalism and metal theft is also a problem for weirs, particularly in urban areas. Significant geometric irregularities, roughening or vegetation growth to the crest of a weir can greatly affect its discharge capacity.

The planning of rehabilitation works should involve a detailed inspection of the condition and performance of the materials making up the weir and allow for removal, repair and replacement where appropriate. Common remedial works include removal of vegetation, cleaning, repointing and patch repair work. Concrete repair to extend the life of the existing weir foundation are also commonly specified.

5.4.6 Deterioration of hydraulic steelwork

Overhaul or complete replacement of hydraulic steelwork is commonly a major component of weir refurbishment projects. A visual survey of the steelwork should be carried out and, where applicable, steel thickness surveys undertaken to determine residual steel thicknesses. These surveys can be used to inform subsequent structural analysis of gates in a deteriorated condition and a decision about residual life and whether replacement or refurbishment is required. Often, gate replacement is the most economic option, as refurbishment usually requires a longer time on site to remove the gates from the weir and to then replace the refurbished gates. For further guidance on the assessment of hydraulic steelwork see ASCE (2012).

5.4.7 Introduction of fish passage or hydropower

The requirement to incorporate new structures within an existing weir commonly relates to the provision of fish passes and low head hydropower.

Under the Salmon and Freshwater Fisheries Act 1975, in waters frequented by salmonids, fish passage must be provided if a weir is *"from any cause has been destroyed or taken down to the extent of one-half of its length is rebuilt or reinstated"*. Improvements to fish passage are often a legally required component of a refurbishment project, and one that can usually be readily accommodated. Fish passage is discussed in further in **Section 11.5**. Specific considerations relating to including fish passes or turbines within weir improvement projects include:

- The need to integrate the new element into an old structure of unknown construction.
- A requirement to preserve the hydraulic capacity of the weir, while adding another structure to the channel (it may be possible to use existing openings, failures or sluices for fish passage).
- In some cases, the need to avoid impact upon a well-established flow gauging record.
- Ensuring compatibility of the new pass with existing operational practices, for instance ensuring that attraction flow is sufficient relative to adjacent gate discharges.

5.4.8 Operation, maintenance and safety considerations

A significant proportion of rehabilitation (and removal) works can result from deferred maintenance. An element of a rehabilitation project should be to review maintenance procedures, programmes and budgets to ensure that the newly refurbished structure is adequately maintained. This also means a reasonable amount of time is given before subsequent refurbishment works. Standardisation of weir type and spare parts across several structures can help maintain a number of weirs more efficiently.

Operational practice should be reviewed including, where applicable, gate operating procedures, water level management requirements, flood risk management, communication protocols and emergency preparedness plans. Where hazards are present they should be managed through a hierarchy of measures, in order of preference, to eliminate, reduce, isolate, and control the hazards. This should minimise risk to as low as reasonably practicable (ALARP) levels. Where manual operation of a gated weir is still required, this should be reviewed to understand the safety of the operation and to assess alternatives such as mechanisation or the provision of portable power packs for gate winding. Task lighting and access provision for operatives should be reviewed.

Public safety should be considered, particularly where there is public access over or near to the weir. Rescue facilities, access for rescue, improvements to hazard signage and safety barriers should be considered, however there should be a balance between discouraging unauthorised access and hindering access for rescue. The hydraulic safety of the weir should also be examined and where necessary improved. In some cases poor weir safety is a good reason for weir removal. Further information on safety is given in **Chapter 10**.

5.4.9 Construction

Dewatering and temporary works provisions can be more involved for weir refurbishment or alteration projects. This is because the existing weir foundation can interfere with the temporary works. Old timber piles, waling beams and shuttering can prove a significant barrier to steel sheet piling (Morris and Simm, 2000) (see **Chapter 15**).

5.4.10 Guidance

There is limited guidance on weir refurbishment, however there is good description of specific rehabilitation projects for larger international structures. For example, Hill (2006) describes the rehabilitation of Assiut Barrage, a major structure on the River Nile in Egypt. The various stages of study are provided, including:

- forensic study to determine the historical development of the structure
- condition inspection of the civil and hydro-mechanical works
- interim remedial measures to secure the structure
- improvements to operational practices
- inclusion of hydropower
- provision for river-borne craft
- comparison of the relative merits of rehabilitation
- wholesale replacement for individual components and for the whole structure.

A range of other project papers are available including, for example, description of the rehabilitation of Kotri Barrage on the River Indus, Pakistan by Padgett and Morrison (2002).

Other rehabilitation case studies are included within this guide (see **Box 13.2**).

5.5 NEW OR REPLACEMENT WEIRS

With proper maintenance and periodic rehabilitation works, a new or replacement weir structure might have a useful life of between 50 and 200 years, albeit with replacement of any mechanical and electrical equipment. Decisions taken during design and construction may be experienced several generations into the future, so it is vital that those responsible for the planning and design of weirs are aware of all of the issues and potential conflicts and they consult interested parties in order to seek the best solution.
The appropriate engineering, ecological and geomorphological expertise should be involved, firstly in the decision to build a new weir, and secondly to ensure that due consideration and judgement is used in the planning and design process so that good practice is adopted.

Many of the issues described in **Section 5.4** are applicable to new-build weirs, especially where the intention is to replace an existing structure. This section briefly describes further some issues particular to new structures. For more information also see **Chapter 7**.

5.5.1 Reasons for a new weir

Construction of major new impounding structures is a relatively rare occurrence in the UK, albeit that there are more examples of smaller weir structures for high head hydropower. It is more usual that 'new' weirs are replacement or substantial replacements of existing structures. A new weir might be considered:

- To replace an existing weir that has deteriorated to a point where it is no longer economic to repair it.
- To replace an existing weir that does not cater for current requirements and is not economically adaptable (eg when excessive manual force is required to operate the weir or effective flood management is not possible with the existing structure).
- Where a new functional requirement has been identified (eg a new abstraction, a tidal barrier or a new flood bypass channel).

5.5.2 Site selection

Where a new structure is proposed there are several important considerations for selection of the site. These will depend on the function of the weir. Considerations include, among other things:

- topography and geomorphology of the catchment
- flooding of upstream infrastructure
- environmental considerations
- geology of the foundations
- material availability
- hydrology
- site access
- ease of river diversion during construction.

These factors should be balanced to find the most economic site for safe construction of the weir to suit the project requirements.

In the UK, infrastructure surrounding the new weir may have developed over many hundreds of years and site selection, particularly in urban areas, usually relates to small-scale adjustments within a prescribed weir location, often associated

with the site of an existing weir that is to be replaced. Further discussion around site selection is provided in **Chapter 14**.

5.5.3 Review of design floods and capacity

For a new weir, or where an old weir is replaced or significantly altered, the hydraulic capacity of the structure should be reviewed. This can be a sensitive topic, particularly in urban areas where the structure will influence the risk of flooding in the reaches of river both upstream and downstream of the weir. Selecting a design hydraulic capacity for a weir is a site-specific exercise, but is usually a matter of considering the acceptable afflux with respect to the topography of the upstream river-banks and the value of the flood receptors present. This process is discussed further in **Chapter 13**.

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6 How should the options be compared?

6.1 INTRODUCTION

The options identified in **Chapter 5** should be assessed to identify which are technically viable, have acceptable impacts on the environment (or impacts that can be mitigated to a tolerable level), and are economically worthwhile. The remaining options are then compared to find the most advantageous option that can be recommended and selected for design. Options appraisal is generally iterative with an increasing level of detail as the work progresses (**Figure 6.1**).

The method of appraisal and level of detail should be proportionate to the size, complexity and risk associated with the project, and the nature and extent of the impacts that may arise. An appraisal should identify a wide range of options to start with and eliminate those that are technically unviable, perhaps due to significant issues ('showstoppers') or constraints on the nature, extent or timing of the work (such as access, buried services or contamination). Options should work with natural processes where possible. Environmentally adverse options should be avoided, considering the environmental impacts of each option on the wider catchment, not just the weir and its immediate environment.

The appraisal should consider changes that may take place during the design life of the asset. It should indicate whether the options should be robust to accommodate a range of future scenarios, flexible to allow alteration to new circumstances in the future, or whether to delay decisions that would be difficult to change.

A cost estimate should be prepared at an early stage to ensure that there is a business case, the scheme is affordable and to allow the project promoter to secure funding in good time.

It is helpful to maintain an audit trail to explain why a given option has been selected or rejected.

The issues associated with options appraisal for weirs typically relate to lack of information. Where part of an asset is submerged or buried, it may not be economic to de-water a site in advance of construction or to use non-intrusive survey techniques, and its condition may remain unknown until construction starts. Information on the location or status of underground services may be poor or inaccurate. It is usual to allow for such uncertainties with an appropriate risk contingency in the project budget. It is also important to allow sufficient time to gather all information, particularly environmental baseline surveys that have to be undertaken at a given time of year.

6.2 TECHNICAL APPRAISAL

Technical appraisal aims to screen out technically unviable options and identify a shortlist of viable options that can be included in an environmental and economic appraisal. The nature and extent of the appraisal will depend on the size of the weir, its complexity and the level of risk (as well as the urgency of the problem), and it may be streamlined for emergency works.

An appraisal should start with high-level options (eg do nothing, do minimum or do something), then consider generic options (eg removal or lowering, repair, modification or improvement, new or replacement weir, and whether alternatives are available that could perform the required functions), and finally specific options (eg replace online or replace upstream of existing weir – fixed or movable weir).

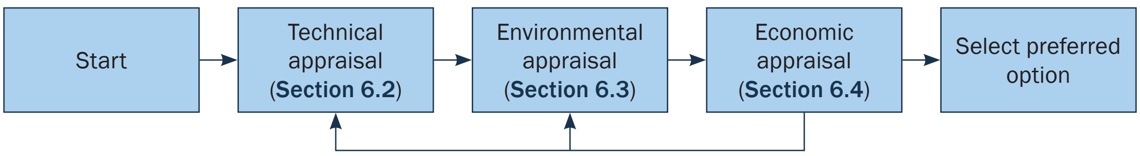

Figure 6.1 Options appraisal process

Box 6.1 *Definition of options*

Options should be compared with a baseline such as 'do nothing' or 'do minimum' in order to determine the merits of taking greater intervention.

Do nothing involves walking away, ceasing all maintenance. A movable weir may have variations such as 'leave gates open' or 'leave gates closed'.

Do minimum involves doing the minimum necessary to meet legal requirements or sustain a standard of service. It may involve doing more than current practice.

Do something involves taking intervention over and above do minimum, and may include maintenance, capital works or decommissioning.

The potential impacts of an option can be assessed qualitatively or quantitatively. The level of detail will vary depending on the stage of the assessment. This may involve hydraulic modelling to assess the impacts on upstream water levels, navigation draught or flood risk, the attraction flow for fish pass, or the location of a hydraulic jump and of the need for a stilling basin. As the options are developed, sketching them onto a plan is useful for environmental and economic appraisal. This should show all of the local design constraints, along with factors that may affect the timing or method of working, choice of plant or materials (eg land ownership, access routes, width, height or weight constraints), potential site compound locations, services and designated sites.

The viability of removal or lowering will be influenced by the function(s) of weir (see **Chapter 3**), the historical or architectural significance of the weir and its setting, and potential adverse impacts (see **Table 6.1**).

Table 6.1 *Factors to consider in technical appraisal (after PIANC, 2006)*

Factor	Sub-factor
Whole-life cost (**Section 6.4**)	Capital Operation Removal
Safety (**Chapter 10**)	Risk to staff, visitors or river users
Environmental and ecological impacts (**Chapter 11**)	Water quality Fisheries Habitat Built heritage Recreation Landscape Noise
Impacts on geomorphology (**Chapter 12**)	Scour Sediment transport or sedimentation upstream Passage of debris
Hydraulics (**Chapter 13**)	Sensitivity of water levels to changes in flow Land drainage or flood risk
Geometry (**Section 13.3**)	Required flow capacity Upstream water levels Available space Fixed or movable crest Size, amount and type of material, hence cost Design complexity Civil works footprint
Operation	Speed of operation Degree of attendance Degree of mechanisation Flow/level control Reliability Access and maintenance Debris management Disruption to navigation Compatibility with asset portfolio

If considering maintenance, repair or improvement, the options will be influenced by knowledge of the construction, materials and condition of the existing structure. In addition, its residual life, future changes (eg due to climate change), and whether the structure will continue to perform adequately despite those changes should be noted. The design life of a repair should not greatly exceed that of the rest of the structure.

For new or replacement weirs, the selection of weir type will largely depend upon the function of the weir and a set of design constraints and requirements determined during the objective setting stage.

A prompt list of factors to consider in technical appraisal is given in **Table 6.1**.

6.3 ENVIRONMENTAL APPRAISAL

An environmental appraisal of the main features and sensitivities of the project area will steer the decision-making process and selection of an appropriate solution. Being aware of the potential issues and sensitivities helps with project planning and programming of the proposed works. The works may not require formal permissions, but other legal requirements may need to be met such as obtaining licences to disturb protected species. This may also have seasonal constraints that could affect the overall implementation programme for the scheme. Equally, though not a legal requirement, if a third party group who may be directly affected by a proposed scheme has not been identified and considered in the development of the options, then there is a risk that potential late changes to the scheme, delays and increased costs may follow. Having developed an appreciation of the main issues associated with a scheme then the opportunities to realise multiple benefits could be explored. For instance, it is possible that a simple change in the way a weir is operated could result in:

- reduced operational liability
- reduced flood risk
- eased fish migration
- increased recruitment and river enhancement both for ecological diversity and landscape aesthetics.

Table 6.2 sets out the broad principles of the potential areas that should be considered at the appraisal stage with a brief commentary setting out the main issues. Note that this is not an exhaustive checklist. More detailed information is given in **Chapter 11**.

Once the information gathering is complete, the evidence for potential barriers to progress or constraints that cannot be mitigated may eliminate options from further consideration. Consultations with the relevant regulating authorities would provide further information to address constraints, which may include legal protection of sites, features or species and required mitigation options.

Where options are still deemed viable, a useful tool to communicate key issues to all parties involved in the project is an environmental constraints and opportunities map. Such a map can be useful during all stages of the project from consultation through to implementing the scheme and should identify all areas where environmental considerations may influence scheme development.

Methodologies for differentiating between options on environmental issues are less well developed than economic appraisal techniques. Methods that could be used include flood and coastal erosion risk management appraisal guidance (FCERM-AG) and the ecosystems approach (see **Section 6.4**, and Environment Agency, 2010b, Rouquette, 2013).

Balancing complex and potentially conflicting environmental issues to select a preferred option can be delivered through a workshop approach where the different interest groups can discuss the relative merits and issues related to options. Good practice needs to be adopted in the approach to any workshops so that the participants are fully informed of the options beforehand and are then able to contribute to the review of alternatives. Objective scoring and ranking of options should follow reasoned expert judgement based on the specific issues.

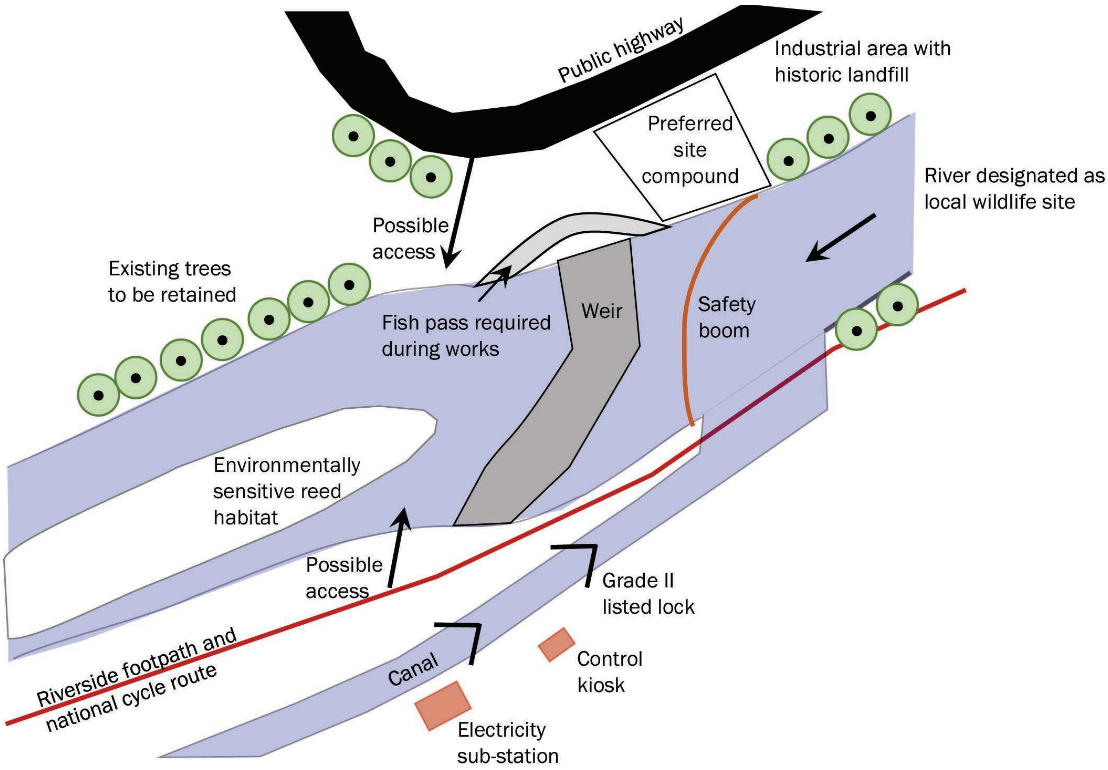

Figure 6.2 ***Example environmental constraints plan***

Table 6.2 ***Checklist of environmental issues***

Issue	Commentary	Further information
Is the site likely to affect navigation? (**Section 9.3.3**)	Establish existing navigation requirements.	Consult the Environment Agency, other regulating authority or LA for further advice.
Is the weir designed to ensure channel stability?	Establish function of weir with regards to grade control and channel stability. Removal or modification to such weir structures may be complex and result in significant instability upstream.	Consult with a geomorphologist, the Environment Agency or LA
Is the site on or near a designated nature conservation site? (**Section 9.4.3**)	Consent may be required. If the development potentially adversely affects the conservation objectives of European or nationally protected sites it will be prohibited or restricted. The competent authority can request an appropriate assessment, which may need several seasons' survey data.	Check the Multi-Agency Geographic Information for the Countryside (MAGIC) website (see **Websites**), which includes European and national designated sites in England, Scotland and Wales. The regional biodiversity centre will also hold the information together with more local designations.
Is the site near or will the work affect any protected species (eg birds, bats, badgers, reptiles or aquatic species)? (**Section 9.4.3**)	A licence may be required. Note that seasonal constraints and specific mitigation measures may apply.	Consult the regional biodiversity centre for specific information on the location of protected species.
Is the site important for fish spawning, recruitment and general fish populations? (**Section 9.4.4**)	Note that seasonal constraints and specific mitigation measures may apply.	Contact Environment Agency or other regulating authority for further advice, as well as the regional biodiversity centre for local biodiversity records and local fisheries groups.
Is the site close to areas of cultural heritage importance, listed buildings, in a conservation area or adjacent to a Scheduled Monument? (**Section 9.4.5**)	Consent may be required for material change to listed buildings, Scheduled Monuments or works within conservation areas. Note that specific mitigation measures may apply and programme implications of achieving consent.	Consult Historic England, Historic Environment Scotland, CADW and Northern Ireland Environment and Heritage Service (EHSNI), NIEA, LA conservation officer (title may vary with different councils) or other regulating authority and associated websites for further advice.

Issue	Commentary	Further information
Is the site close to or within a protected landscape, park or garden? (**Section 9.4.5**)	May be a material consideration for planning consent	Consult MAGIC website, Historic Wales, Scotland's Environment, Department of the Environment Northern Ireland (DOENI) and PastMap (see **Websites**), or the LPA local plan.
Will the work require the removal of vegetation, trees and hedgerows? Are there any Tree Preservation Orders (TPOs)? (**Section 9.4.5**)	Consent may be required in conservation areas, if the trees are protected by TPOs and if hedgerows fall under the Hedgerow Regulations 1997. Pruning, uprooting or felling of non-protected trees may require a tree felling licence. If planning permission is granted, these requirements are superseded, but should inform the decision-making process for the design of the works.	Consult the regional biodiversity centre or the LA ecology or tree officers for specific information on the location of historic important hedgerows, TPOs or conservation areas.
Is the site on or near contaminated land? Is there evidence of wastes dumped/fly-tipped? (**Sections 9.4.6 and 9.4.7**)	Specific management and mitigation measures may be required.	Consult the Environment Agency or other regulating authority for further advice.
Presence of invasive species that may be spread by increased connectivity (**Section 9.4.8**)	Specific management and mitigation measures may be required to prevent the spread of invasive species because of the works.	Consult the regional biodiversity centre, LA ecology officer, Environment Agency or other regulating authority for further advice.
Is formal consent required? (**Section 9.7**)	Works in or adjacent to main rivers generally require consent from the regulating authority. Works in England in or adjacent to watercourses maintained by the local Internal Drainage Board (IDB) require land drainage consent from the relevant IDB. Consent is required from the lead local flood authority (LLFA) for work on or adjacent to ordinary watercourses.	Contact the regulating authority for further advice (Environment Agency, SEPA, NRW and NIEA, IDB or LLFA).
Are there any WFD requirements for your channel (ecological, physicochemical and geomorphological factors)? (**Section 9.7.1**, **Chapter 12**)	No deterioration of a waterbody is allowed. Works should not prevent the waterbody reaching 'good' or 'potential' ecological status by 2027.	Consult regulatory authority for further advice.
Is planning permission required? (**Section 9.7.4**)	If the scheme falls within the 'development' definition under the Town and Country Planning Act 1990 then planning permission would be required from the local planning authority (LPA).	Contact the LPA for further advice.
Is an Environmental Impact Assessment (EIA) required for the project? (**Section 9.7.4**)	The criteria for whether an EIA is required are set out in the Town and Country Planning (Environmental Impact Assessment) Regulations 2011 based on Directive 2009/31/EC (EIA Directive). Note that 'permitted development rights' are withdrawn if an environmental assessment is required.	Contact the regulating authority for further advice.
Is the site in close proximity to residential properties or publically accessible areas that would be directly or indirectly affected by the scheme? (**Section 11.7**)	Consultation with third parties may be required. Noise control measures and licences may be required.	Check the MAGIC website (see **Websites**) or the LPA local plan documents.
Are there third party groups or individuals that would be directly affected by the scheme? (**Section 11.7**)	Establish if passive and active recreation activities would be affected by the potential scheme	Consult Environment Agency or other regulating authority or LA for further advice.
Would recreation be affected? (**Section 11.7**)	Establish user groups and provide appropriate safety measures.	Consult British Canoeing, British Rowing or other recreation bodies (see **Websites**).

Websites

British Canoeing: **https://www.britishcanoeing.org.uk**

British Rowing: **https://www.britishrowing.org**

DOENI: **www.doeni.gov.uk/niea**

Historic Wales: **www.Historicwales.gov.uk**

Multi-Agency Geographic Information for the Countryside (MAGIC): **http://magic.defra.gov.uk**

PastMap: **www.pastmap.org.uk**

Scotland's Environment: **www.environment.scotland.gov.uk**

6.4 ECONOMIC APPRAISAL

Economic appraisal is a tool to guide investment decisions and allows options to be compared using money as the common unit of measurement, although it may also be necessary to assess other outcome measures for flood risk management projects seeking Defra funding in England and Wales. The appraisal method chosen should be proportionate to the type of project, the stage of the assessment and the importance of the decision.

Do something options should be compared with a baseline option that will vary depending on the nature of the assessment. If the work is mandatory and all options must achieve regulatory compliance, then the baseline will be 'do minimum'. If the work is not mandatory, then 'do nothing' may be chosen, although for movable weirs, this may encompass several variations (**Box 6.1**). If the cost of regulatory compliance exceeds the benefit of retaining the asset, it may be worth considering whether it is possible to remove the asset.

Whole-life costs and benefits should be estimated, focusing time and energy on those that are likely to be most significant and taking care to avoid double-counting. Discounting to present value takes into account time preference, a preference to receive goods or services now rather than later. However this approach has been criticised for giving undue weight to short-term benefits although this depends on the discount rate (HM Treasury, 2011).

Uncertainty, particularly in the early stage of a project or when dealing with assets that are submerged or buried until the time of construction, can be accommodated either by adding optimism bias as a percentage of whole-life cost (for initial assessments) or by adding a contingency sum or using a risk register for detailed assessments (HM Treasury, 2011). Uncertainty in benefits should be assessed by sensitivity testing (Environment Agency, 2010b).

Some economic appraisal methods appropriate to weir projects are summarised in **Table 6.3** with further detail in the following paragraphs. Impacts may be assessed qualitatively (eg positive or adverse, no impact, minor impact or major impact) or quantitatively.

Whole-life cost encompasses the capital cost of construction, plus operation, inspection and maintenance costs, and the cost of asset removal, whether for recycling or disposal. A substantial part of the construction cost of a weir can relate to temporary works (such as access or water management) which should be explicitly planned and provided for in the estimate from an early stage.

At strategy or feasibility stage, approximate methods such as engineering judgement, experience of similar work, benchmarking against previous projects, historical unit rates and cost curves are appropriate, but carry a degree of uncertainty. This can be offset by a contingency sum or optimism bias (mean cost over-runs based on real data, as a percentage of cost) (HM Treasury, 2011). As design progresses, more detailed cost estimates can be built up from labour, plant and materials (using the activities involved, quantities of work and productivity data), or bills of quantities (estimated quantities and market rates, either from a published price book or ideally through early contractor involvement). These will be accompanied by a detailed contingency sum, often based on a risk register and for large projects quantitative risk analysis using, for example, Monte Carlo analysis. This assessment should involve the experience of the whole project team, and ideally major parts of the supply chain.

Some cost estimation methods and data specific to weirs are given in **Table 6.4**. The high cost of principal inspection highlights the importance of considering how an asset will be inspected during the early design stages so that future inspection costs can be minimised.

The whole-life benefits (or damages avoided) and impacts associated with weirs are diverse and some sources of benefits data used in the UK are given in **Table 6.5**.

Table 6.3 *Summary of economic appraisal methods*

Method	Applications	Description	References
Appraisal summary tables	Minimum requirement. Strategic assessment, feasibility studies or small projects.	Tabulate impacts and benefits, issues and opportunities, who may be affected and/or benefit, risks and assumptions.	Environment Agency (2010b)
Scoring and weighting	If non-monetised benefits are significant, impacts fall out with existing guidance, or insufficient information is available for monetary appraisal.	Assign scores and weights to impacts of each option, generate monetary values for intangible impacts using the estimated values of tangible impacts.	Environment Agency (2010b)
Ecosystem approach	If works are likely to affect the environment or have multiple objectives.	Assess changes to ecosystem services because of each option, using scoring and weighting or quantitative assessment.	Defra (2007) and (2015) Rouquette (2013)
Cost-effectiveness analysis	If works are mandatory and asset owner needs to compare ways of fulfilling legal obligations.	Monetised method to determine least expensive option that will achieve the objective(s). Assumes equal benefits for all options.	HM Treasury (2011) Snell (2010) Environment Agency (2010b)
Cost-benefit analysis	If works are not mandatory and the asset owner needs to choose between doing nothing and doing something.	Compare whole-life costs and benefits (or damages avoided) of options, using benefit-cost ratio, net present value (NPV) or internal rate of return. May be economic (from the perspective of the economy) or commercial (from the perspective of the appraising organisation).	

Table 6.4 *Cost estimation methods and data for weir works*

Type of work	Data/method	Reference
Removal, lowering or failure (**Section 5.3**)	Typical cost breakdown: ■ 30 per cent infrastructure removal or deconstruction ■ 22 per cent environmental engineering or enhancement ■ 48 per cent sediment management	Nissen *et al* (2005)
	Kentchurch Weir, River Monnow: ■ removal of 2.6 m high weir ■ £100 000 total, of which £60 000 demolition Padiham Weir, River Calder: ■ weir lowering and rock ramp construction of 1.85 m high weir: £206 000	RRC (2013)
	Cost of several weir removals in Spain: £17 500 to £80 000	De Leaniz (2008)
	Removal costs of 131 dams and weirs in the USA	Nissen *et al* (2005)
	Removal costs of 36 dams and weirs in the USA	Heinz Center (2002)
	20 to 50 per cent of repair cost	American Rivers *et al* (1999)
	For weirs up to 3 m high, removal cost < 20 per cent of cost of Denil fish pass, and < 12 per cent of cost of pool and traverse fish pass	Elbourne *et al* (2013)
	Mitigation of failure typically less cost-effective than removal, unless weir has been designed to fail safely (see **Section 12.4.3**)	Elbourne *et al* (2013)
Refurbishment, repair or improvement (**Section 5.4**)	No data on capital works, probably due to the unique nature of projects	Heinz Center (2002)
New or replacement weirs (**Section 5.5**)	Equation for re-construction of movable weirs based on ten movable weirs in France	PIANC (2006)
	Equation for construction cost based on eight weirs worldwide, including Thames Barrier	Van der Toorn (2010)
Inspection and maintenance (**Chapter 8**)	Visual inspection and maintenance: £100 per asset per year Principal inspection: depends on standard of inspection (eg £250 000 for de-watering large river weir)	Canal & River Trust (pers. comms.)

Table 6.5 Sources of benefits data

Type	Description	References
Built heritage	Conservation of built heritage	None
Channel stabilisation	Change in need for bank protection or dredging	None
Fisheries and ecology	Fish and eel migration or diversity	Brouwer *et al* (2010), Penning-Rowsell *et al* (2013)
Flooding	Direct damage to residential and non-residential properties, or infrastructure	Penning-Rowsell *et al* (2013), FHRC (2016)
	Indirect damage due to cost of emergency services, road and rail disruption	
Habitat	Diversity of habitat for plants, wildlife, aquatic invertebrates, fish	CIRIA (2015), Penning-Rowsell *et al* (2013), Brouwer *et al* (2010)
Hydropower	Electricity generation and sale of surplus to National Grid	UK Government (2014)
Land drainage	Agricultural production	Penning-Rowsell *et al* (2013), FHRC (2016)
Land value	Premium on waterside properties	O'Gorman *et al* (2009), CABE (2009)
Navigation	Transfer road or rail traffic to water	O'Gorman *et al* (2009)
Recreation	Health benefits due to physical activity (eg angling, canoeing)	CIRIA (2015), Penning-Rowsell *et al* (2013), FHRC (2016), O'Gorman *et al* (2009)
Safety	Hazard, injury and loss of life	HSE (2014a)
Visual amenity	Change in visual amenity	O'Gorman *et al* (2009)
Water quality	Plant, wildlife or fish species diversity, or suitability for boating and swimming	O'Gorman *et al* (2009)
Water supply	Water sales, reduced need for pumping and treatment	O'Gorman *et al* (2009)

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7 Design, implementation and monitoring

7.1 INTRODUCTION

This chapter gives an overview of design, implementation and monitoring of a new weir project, although much of the material is also relevant when considering removal of an existing weir, alternatives to a weir, modification or replacement of a weir, or indeed any works in a river channel. Further, more detailed guidance on the various topics introduced is provided in **Part 3**.

7.2 DESIGN

The relentless flow of a river as it travels from its source to the sea has incredible power to erode and shape natural landscapes. Unharnessed, a river will try to move over time as natural processes allow it to change its path and grade to reach equilibrium with its environment. A weir (and the concentrated head drop across it) can present a significant imbalance to this equilibrium. Over long periods of time, a weir will be subjected to the natural forces of the river, which will strive daily to erode, undermine, circumnavigate and otherwise remove the structure in its path. Weirs should be carefully located, designed, constructed, monitored, maintained and adapted as necessary in order to remain functional and safe over their design life.

This chapter addresses the general considerations for design of a weir and highlights some more detailed issues that have particular resonance across disciplines. Further more detailed guidance for design can found in **Part 3** of the document.

In general, the technical design of a weir can be split into:

- geomorphological design (**Chapter 12**)
- hydrology and hydraulics (**Chapter 13**)
- foundations and geotechnical (**Chapter 14**)
- structures and materials (**Chapter 14**).

All design should be carried out with the avoidance of risk in mind and following a hierarchy of risk control. In the UK, the designer must comply with duties set out in the Construction (Design and Management) Regulations 2015 (CDM 2015) and follow the measures set out in the guidance that accompanies the Regulations (HSE, 2015).

Figure 7.1 illustrates the main components of a weir and the technical terms used to describe them.

The process of selecting a preliminary weir geometry will vary with the type and function of the weir. In addition, the general approach to initial hydraulic and foundation sizing is shown in **Figure 7.2**.

There is close interaction between hydraulic design, energy dissipation, foundation design and practical construction issues particularly in terms of temporary works and construction plant, so a comprehensive and iterative approach to weir design is particularly important. The main issues that need to be considered during design are listed in Table 7.1, with further detail in Part 3.

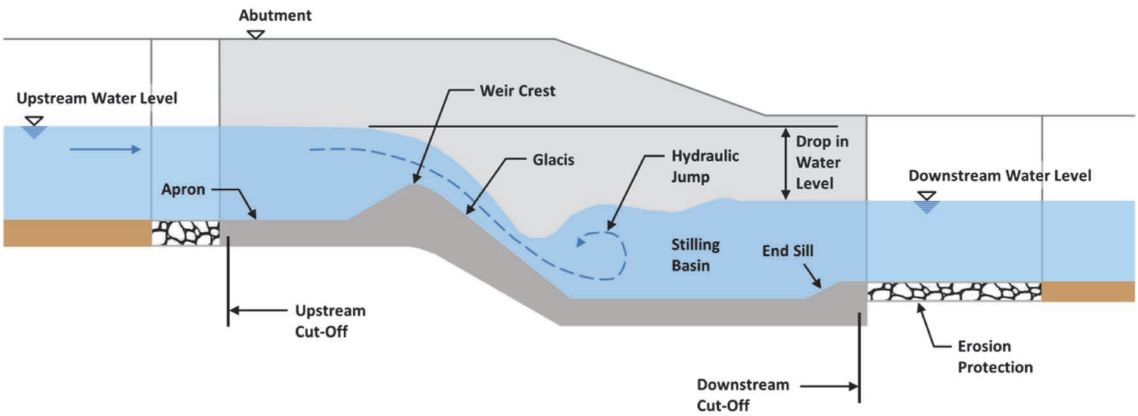

Figure 7.1 Main components of a weir

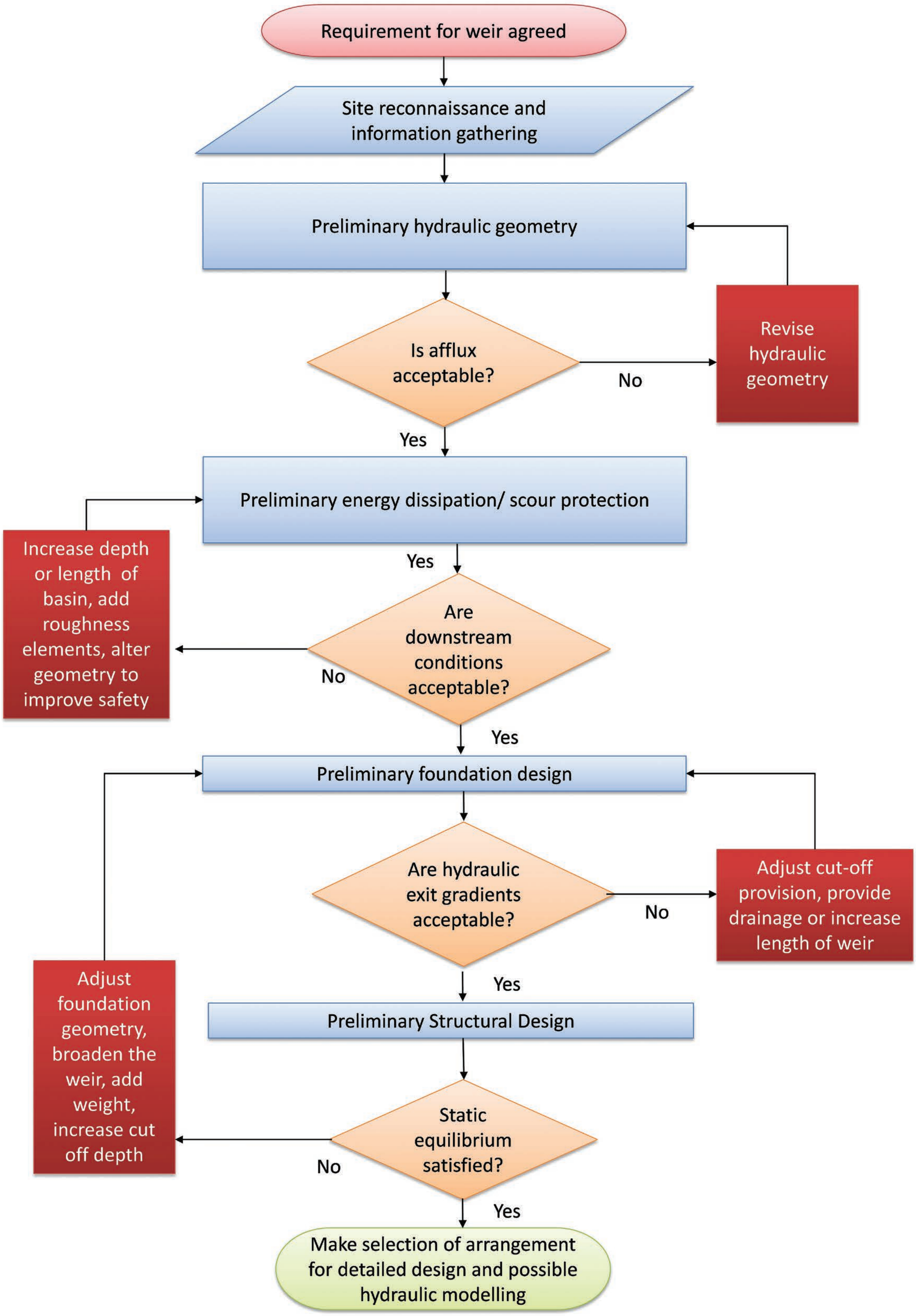

Figure 7.2 Process of preliminary weir sizing

Table 7.1 Checklist of design issues

Type	Issue	Commentary
Access (Section 15.4)	Access constraints due to working in or near watercourse	Access to remote areas Site compound ideally on high ground Access upstream and downstream of weir may involve tracking through deep and/or fast-flowing water or re-circulating flow Risk of flooding of the access and/or works Maintenance of flow to watercourse downstream
Construction safety Section 15.3)	Design to reduce hazards during construction	Work in or near water Potential conflicts between site traffic and the public Maintain or divert public rights-of-way during the works
Operational safety (Chapter 10)	Design to reduce hazards and risks to unauthorised and authorised users	Hazards (hydraulic, underwater, chemical, biological) Likelihood of harm (signage, barriers) Ease of self-rescue or assisted rescue Mechanical and electrical safety Operational safety (access, guarding, visible or audible warnings, manual handling)
Environment, ecological and habitat design (Chapter 11)	Opportunities to provide ecological and habitat improvements or mitigations around the weir should be considered during the design process	These might include fish passes, otter ramps, bypass channels for fish and canoe passage and provide shallow flowing water habitat. Habitat enhancements might include river restoration techniques or perhaps improvements in lateral connectivity between the river and riparian habitat in the floodplain
Stakeholder aspirations	Opportunities to meet the aspirations of stakeholders for the weir and surrounding environment	Leisure/amenity features Landscape Access
Geomorphological design (Chapter 12)	Assessing impacts on geomorphological forms and processes (Section 12.3)	Geomorphological assessment
	Avoiding impacts on geomorphological forms and processes (Sections 12.3 and 12.4)	Alternatives to weir structures to achieve the desired influence on water levels upstream without construction of a weir
	Reducing impacts on geomorphological forms and processes (Section 12.4)	Geomorphological design measures to reduce impact
General hydraulic arrangement (Chapter 13)	Weir location (Section 14.2)	Considerations for macro and micro-scale location
	Weir capacity and acceptable afflux (Chapter 13.3)	Selecting weir capacity and pond level to prevent out-of-bank flow for a given return period flood and to avoid impeding drainage to areas upstream
Hydraulic design (Chapter 13)	Hydraulic design and hydraulic modelling (Section 13.5)	Hydraulic modelling and design of a suitable hydraulic arrangement for the weir to meet the functional requirements of the project
	Energy dissipation (Section 13.6)	The design of safe and effective hydraulic stilling arrangements
	Scour and scour protection (Section 13.7)	Assessing scour depths and the requirements for scour protection
Design resilience	Future proofing and whole life design	Flexibility to accommodate future advances in technology should be considered during design. Resilience to changes in environment around the weir can be built into the design. For instance additional capacity can be included to accommodate potentially higher future flows (although this often is determined by the river channel capacity rather than the weir capacity). Consider how the weir will be eventually decommissioned and the effect of removal of the weir on future river morphology

Type	Issue	Commentary
Foundations and geotechnical design (**Chapter 14**)	Static equilibrium (**Section 14.3**)	Actions destabilising the structure (typically the retained water and pressures acting under the weir) must be balanced by restoring actions (typically the weight of the weir structure and resistance provided by the ground underneath the structure)
	Hydraulic failure (**Section 14.3**)	Design against hydraulic failure caused by seepage: avoiding piping and uplift conditions under and around the weir
	Other geotechnical considerations (**Section 14.3**)	These aspects may include settlement (in particular differential settlement if the weir is gated as structural movement can cause gates to seize), bearing capacity of the supporting strata and the need for ground treatment or supporting piles under the weir
Materials (**Section 14.4**)	Selection of suitably robust materials to avoid premature failure of the weir structure. Visual appearance and economic and sustainable material selection	Historically weirs were typically constructed from timber, rough stone and masonry materials and these materials are often encountered during weir removal or refurbishment projects. Modern weirs almost invariably involve some form of concrete construction, although a large variety of materials can be used depending on the size and type of weir and the local environment
Structures (**Section 14.5**)	Design of the superstructure of the weir built onto the foundation	Coded and non-coded structural guidance Bridges, walkways, piers, wingwalls, hydraulic gates and other appurtenant features
Operation and maintenance (**Chapter 8, and Section 14.5**)	Design for future operation and maintenance of the weir	Safe access for inspection and routine maintenance. Safe access to and from the weir, walking surfaces, edge protection and task lighting Operational requirements, speed of operation, trash clearance, water level control, instrumentation, system redundancy and back-up, system standardisation

There are many issues to be considered when planning and implementing works on weirs. Also, it can be difficult to design works on weirs that will fully satisfy the aspirations of all parties who have an interest in the weir or the reach of river in which it is located. Inevitably there will be instances where there are conflicts of interest. For example, a weir that is ideal for discharge measurement may not be ideal for fish migration, or a weir that is ideal for fish migration may prove less acceptable to canoeists.

It is important to realise that, in recognising the constraints, it should be possible to identify opportunities when looking at the options available. For example, a weir that has both adequate provision for fish migration and safe passage for canoeists can be designed. There are in fact a growing number of multi-use passes constructed in the UK to allow good passage conditions for both fish and canoeists around weirs. Alternatives to weirs can mitigate some of the conflicts.

What is important is that those responsible for planning and implementing works on weirs are aware of all the issues under consideration and act as an integrated team together with the relevant stakeholders and user groups. This is in a large part the purpose of this guide as set out in **Chapter 1**.

7.3 IMPLEMENTATION

Construction of a river weir structure is not inherently far different from conventional civil engineering construction. The critical difference is that throughout the design and implementation process the project team designer must be aware of and plan to manage the construction risks that result from working in or near to the river. Areas that generate substantial construction risk are:

- high river flows
- high river levels
- ground conditions
- constrained access to site for people and plant.

Morris and Simm (2000) provide a detailed guidance manual for risk management in river and estuarine engineering, which is relevant to weir construction and includes many examples of past river weir projects. A brief summary of some of the pertinent issues is given in Chapter 15, however, the reader is referred to Morris and Simm for a detailed treatment of the subject.

The main issues that need to be considered during implementation are summarised in **Table 7.2**, with further detail in **Chapter 15 of Part 3**.

Table 7.2 Checklist of implementation issues

Issue	Commentary
Procurement (Section 15.2)	Engaging professionals at an appropriate stage of the project to foresee and manage risk. Contractual arrangements for apportioning risk and resources to manage risk. Proper timing of procurement with regards to river flows.
Risk management (Section 15.3)	Typical areas of risk for weir projects. Development and use of a risk register to actively manage project risk.
Managing access (Section 15.4)	Weir sites are often difficult to access, and access may incur negative environmental impacts. Access requirements should be identified early on in the project.
Temporary works and construction flood risk (Section 15.6)	Understanding how the weir will be built and the temporary works that will be required. The importance of considering temporary works and river diversion during design. Construction programming, seasonal construction and the impact of delay in terms of flood risk. Flood risk management and protocol during construction. Importance of aligning the contract with flood management measures.
Environmental impact of construction activities (Chapter 15)	The environmental impact of construction works. Access routes in and alongside the river, sensitive ecological conditions and working within the wider river environment. Measures to manage impacts such as noise and vibration, sediment, dust, fish-rescue, spills and control of invasive species.
Adjacent activities during construction works (Chapter 15)	As with all construction sites, nearby activities should be considered during construction planning for a weir project.

7.4 MONITORING

Routine monitoring may be used to inform maintenance and determine the need for intervention. Monitoring following works on weirs may also be required as a condition of consent to work in watercourses, fish pass approval or impoundment licensing (see **Section 8.4**).

7.5 REFERENCES

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Statutes

The Construction (Design and Management) Regulations 2015 (CDM 2015)

Part 3
Detailed guidance

8 Asset management

8.1 INTRODUCTION

Asset management aims to optimise long-term performance and maximise benefits while reducing costs, impacts and risks and can be defined as *"the co-ordinated activities of an organisation to realise value from its assets"* (ISO 55000:2014). This chapter gives an overview of asset management activities specific to weirs. For general guidance on asset management, see Hooper *et al* (2009).

As a minimum, weir owners must take reasonable steps to protect people from harm and avoid adverse impacts on the environment. They must also keep the weir clear of anything that could increase flood risk or jeopardise structural integrity that may endanger the safety of others, such as debris. Weir owners may also need to ensure that a weir fulfils its functions, perhaps to meet contractual obligations to others. It may be necessary maintain a weir to a target condition to prevent defects affecting performance and safety, and avoid excessive deterioration and costs in the future.

The weir management cycle in **Figure 8.1** defines drivers for changes and objectives (**Chapter 3**), and considers the need to intervene (**Chapter 4**).

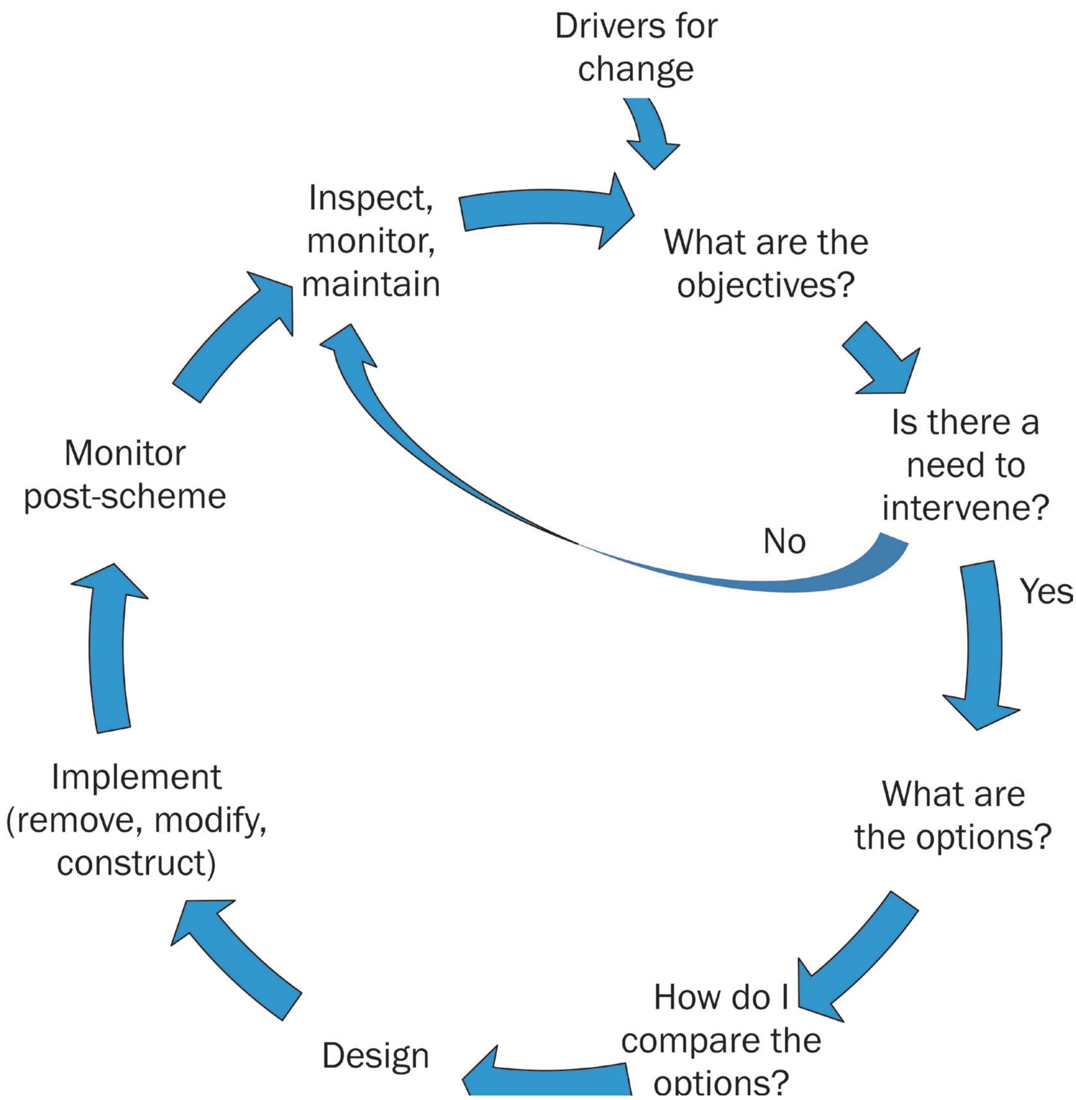

Figure 8.1 Weir management cycle (from RRC, 2013)

If there is no need to intervene, inspection and maintenance should be undertaken at intervals (**Sections 8.2 and 8.3**). Monitoring may be required to determine the rate of deterioration and optimum time for intervention (**Section 8.4**). For all of these activities, access and water management may be needed (**Section 8.5**).

If there is a need to intervene, option identification and appraisal (**Chapters 5 and 6**) may lead to design and implementation (construction, modification, replacement or removal) (**Chapter 7**).

In **Figure 8.1**, the length of each phase is not proportional to actual duration. In practice, inspection and maintenance is the longest phase and may last for centuries, while design and implementation are relatively short. However, they can have a significant effect on the ease of operation and whole-life cost of an asset.

8.2 INSPECTION

Inspection is the close examination of a structure and may be required to:

- determine whether a weir performs adequately
- establish a baseline condition for comparison with future inspections
- identify defects and changes since the last inspection
- assess overall condition and compare this with required condition
- comment on compliance with and adequacy of the maintenance plan
- identify work needed to meet functional requirements
- gather dimensional information
- compare structure performance with the requirements of new or amended legislation or policy.

There are five broad types of inspection although many asset owners have their own terminology (**Table 8.1**). The frequency of inspection should be risk based and depends on the type, function and importance of a weir, the severity of the conditions to which it is exposed, the consequences of failure and its condition at the last inspection. These factors also inform the trigger levels for action, and decision making when considering the need to monitor or intervene.

Table 8.1 Types of inspection for weirs

Type	Description
Safety inspection (see **Table 8.4**)	Regular inspection to identify hazards and defects that may affect public or operational safety, including routine maintenance of safety signs, barriers or rescue equipment
Superficial inspection	Regular walkover inspection to identify defects, changes in condition or unusual features
Visual (general) inspection	Routine inspection to identify hazards and changes in condition Assess surface details and condition Compare photographs with those from previous inspections – ideally take photographs from the same viewpoint in successive inspections Consider using drones at hazardous weirs
Detailed (principal) inspection	Periodic non-intrusive inspection to obtain detailed record of structure condition Inspection of all visible parts of the structure within touching distance. May include hammer testing for voids or loose materials May include underwater inspection by divers for underwater defects and scour (see **Box 8.1**)
Special inspection	In response to known or suspected defects, or adverse conditions such as flooding, scour, debris accumulation Determine whether operation or safety has been affected, any work is needed and to record the observed water level

Box 8.1 Safe diving practice

> Safe diving practice is particularly pertinent for weir work, where head differential across the weir structure, fast flows, cold water and unknown underwater hazards can present significant danger to those carrying out the work, particularly at gated weirs. Diving fatalities, when they occur, are sobering reminder of the duty of care and the importance of proper planning, management and execution of diving work by competent individuals.
>
> Diving for inspection and construction work must be carried out by suitably-qualified contractors and in accordance with the Diving at Work Regulations 1997. An approved code of practice (CoP) and guidance document and other relevant material is available from the Health and Safety Executive (HSE, 2014b). Specialist advice should be sought from commercial divers.

Before embarking on inspections, the target condition grade for a weir should be defined. Examples are given in **Table 8.2**.

Prompt lists for safety inspections and defects commonly found at weirs are given in **Tables 8.3 and 8.4**.

Defects should be reported in a consistent manner to ensure that any changes in condition can be detected by comparing two inspection reports. It is helpful to use standard terminology for defects, extent and severity. An inspection report should follow a methodical route around a structure and it may be necessary to break a large and/or complex structure down into sections. It can be helpful to use a geographical orientation to describe the sections of a weir (eg north apron, south apron) and standard terminology for asset type and materials. Many inspection reports permit the inclusion of photographs which greatly assists in the monitoring of various elements. Crack monitoring tell-tales can provide information on whether cracking is active or dormant and the rate of change.

The condition grade should be compared with the required condition grade to determine whether action is required (**Table 8.6**). The condition grade of a weir can be determined either using engineering judgement or by applying scoring and weighting to each element to indicate its importance to overall performance and function. However, if a critical element falls below target, the whole asset should be shown as below target.

The urgency of intervention is influenced by the condition grade, rate of deterioration and consequences of failure. The rate of deterioration depends on the type of weir, severity of exposure conditions and maintenance regime, and can be inferred from successive inspection reports. Alternatively, three rates of deterioration for fixed weirs based on interviews with practitioners and comparisons between structure age and condition for existing weirs are given in Table 8.6. Deterioration models can be used to predict the time taken for the structure to deteriorate from new to the specified condition grade (and of the residual life of a weir). A basic model for fixed weirs is given in **Table 8.7** and more detailed guidance is available in Halcrow Group Ltd (2013). The design life of a weir is estimated to range from 50 to 200 years with a typical design life of 100 years (although the mechanical and electrical components will have shorter design lives).

For river weirs, weir collapse or failure to function could create a hazard to boaters if the river is navigable or lead to failure of riverside banks and walls. The consequences of failure have a seasonal component and will vary (for movable weirs) on whether the gate fails in the open or closed position. Influential factors include the function of the weir, its location and dimensions, the timing of failure and stored volume of water and sediment, as well as the land use downstream. The proximity of the point of access for boaters to the weir, the possibility of flooding and/or scour, and the effect of rapid drawdown on property upstream should be considered. The geomorphological adjustment following failure of a weir structure could result in increased flood risk, such as through releasing a significant volume of sediment downstream that blocks the channel and elevates water levels.

Table 8.2 Example condition grades (after Canal & River Trust, 2014, and Environment Agency, 2006b)

Grade	General
1 Very good	Sound construction, cosmetic defects with no effect on stability.
2 Good	Minor defects, but structurally sound.
3 Fair	Minor defects that may develop into structurally significant defects in the long term (>10 years).
4 Poor	Structurally significant defects leading to potential loss of stability in the medium term (5 to 10 years).
5 Very poor	Failed or in an incipient state of failure or about to collapse in the short term (<5 years).

For canal weirs, consequences could include overtopping of the canal or breach of the canal embankment, as well as movement of sediment that could be contaminated. On a contour canal or leat with properties below, the consequences are higher than for a similar height of weir on a river where the river channel would provide a conveyance route for water. The main parameters to consider are the length of pound (the length of canal between two locks), escaping water volume, the number of sluices or weirs in the pound, the relative importance of the weir in question, crest length, proximity to inflows, embankments and urban areas, and operational knowledge.

Recommendations for maintenance or intervention should include cost estimates of works to help inform a business case for funding and it may be necessary to prioritise works due to funding or other constraints.

Inspection reports should be retained as they can provide an invaluable guide on changes in condition and the rate of deterioration for future reports. Asset management standards often define how long the reports are kept for. Inspection reports should adopt the same format so that comparison of inspections is simple. Some asset owners develop an in-house proforma for efficiency, to ensure consistency of reporting and to act as an aide memoire. Hand-held devices with bespoke software can streamline the transfer of data to an asset management system.

Table 8.3 ***Prompt list for safety inspections (after Environment Agency 2006b, and Canal & River Trust, 2014)***

Aspect	Description
Safety (**Section 10.2**)	Check operation of drawdown sluice Presence of hazards (hydraulic, physical, chemical or biological)
Signage and warning systems (**Section 10.3.3**)	Warning signs for land or water-based users Manual warning boards or traffic lights Audible or visual alerts at movable gates
Physical barriers (**Section 10.3.3**)	Safety boom upstream of weir and overhead warning signs Safe egress point and portage around weir for canoeists and/or safe moorings for boaters Partial or full exclusion fencing
Monitoring (**Section 10.3.3**)	CCTV monitoring (if unauthorised use an issue)
Self-rescue or assisted rescue (**Section 10.3.4**)	Break in hydraulic jump to allow self-rescue. Deep weir pool for safe passage over weir (whether planned or unplanned) Egress points on both river-banks Access to weir from land and water Grab rails and/or ladders Rescue equipment (eg life buoys, throw lines) Harness attachment points or rope belay points (see **Figure 10.10**)

Table 8.4 ***Prompt list for defects (after Environment Agency 2006b, and Canal & River Trust, 2014)***

Aspect	Description
Weir structure	Crest level uneven or damaged, indicating undermining or movement Leakage through crest or around structure, indicating loss of fill Turbulence on apron indicating loss of face material, holes or scour Cracks or movement of wing walls or abutments
Vegetation	Vegetation growth within or near weir structure
Scour	Undermining or movement of apron toe due to local scour Bank erosion around the weir due to overbank flow Drop in ground level near weir indicating piping failure
Sediment and debris	Sedimentation upstream indicating lack of sediment continuity Accumulation of vegetation or rubbish upstream Blockage of fish pass

Table 8.5 Condition grades for weirs

Grade	Specific description
1 Very good	Crest horizontal with uniform flow Structure stable and free from cracks, erosion or other damage No erosion around the sides of structure or evidence of leaching Upstream face free from silt build-up
2 Good	Crest sound with even depth of flow Structure shows superficial deterioration or cracking. Some perishing. No corrosion or staining Minor erosion or loss of revetment around sides of structure or at end of wingwalls Upstream face shows minor siltation or vegetation growth
3 Fair	Crest slightly uneven with minor settlement Structure sound, but minor, structurally insignificant cracking or mortar loss. Minor staining, vegetation build-up or leakage. Corrosion present, but no loss of section Abutments or wingwalls have minor lateral movement Erosion of channel around sides of structure with potential to undermine stability. Undercutting of training walls or downstream revetment Upstream face shows siltation or vegetation growth. Reduced weir capacity
4 Poor	Crest flow non-uniform with loss of masonry units and effective crest level Structure stable, but significant loss of blocks, spalling, perishing, leakage, structural cracking, deformation, potential loss of stability. Corrosion substantially reducing size of structural members Scour below spillway or at back of wingwalls. Settlement or rotation of crest and wingwalls Major erosion around sides of structure. Water bypassing or leaching through sides
5 Very poor	Crest severely deformed and cracked Structure unstable with severe undercutting and erosion. Corrosion such that significant reduction in size of structural members causing overstressing Loss of wingwalls or apron through erosion of channel sides. Loss of structural integrity Derelict. Potential risk to upstream waterbody

Table 8.6 Rates of deterioration for weirs

Low	Medium	High
Location in channel and catchment appropriate Design, construction and materials appropriate to function and environment Stable foundation and suitable scour protection	Intermediate	Extreme environment: heavy debris or silt load, or gravel and cobble bed Poor quality design, construction or materials Poor maintenance upstream of weir

Table 8.7 Deterioration model for river weirs (medium deterioration rate) (after Flikweert et al, 2013)

Expected deterioration time from new to condition grade (years)	Maintenance regime (see Table 8.8)		
	Do minimum	*Medium*	*High*
1	0	0	0
2	15	30	45
3	20	50	80
4	40	70	100
5	60	90	120

8.3 MAINTENANCE

Maintenance encompasses the work needed to keep a weir in its target condition and includes the removal of debris with the potential to affect performance, vegetation clearance, sediment management and minor repairs. The frequency of each task depends on the target condition grade, although this may be adjusted according to the inspection findings. If inspections are routinely reporting the absence of defects and little deterioration, it may be possible to reduce inspection frequency. Examples of maintenance regimes for weirs are given in **Table 8.8**.

The accumulation of debris (sediment, vegetation and man-made materials) at a fixed or movable weir can affect flow measurement and prevent the operation of gates. It can also increase water levels leading to high risk of overtopping or flooding, or cause erosion due to flow bypassing the structure. It may also accumulate at safety booms, forming large floating rafts upstream, creating an attraction to children and a hazard to navigation, or fish passes, affecting operation. The risk of debris accumulation depends on availability of debris, likelihood of delivery to the weir, weir dimensions and levels, and flow characteristics. Potential sources of debris and risk factors leading to high debris load are given in **Table 8.9**.

If debris becomes trapped against a structure, it should be removed immediately because of the impact it could have on upstream water level and flood risk, as well as flow patterns and local scour. Opportunities to relocate woody debris downstream of the structure should also be considered. Removal is the most common response, but it is recognised that this can have adverse effects on the environment. Alternatives are reducing the probability of blockage or reducing debris load upstream. Methods are summarised in **Table 8.10**.

Vegetation growth on or near a weir structure can, if left unchecked, damage the structure and lead to failure, or at the very least, affect the rating curve of a gauging weir. Fine sediment accumulations (typically upstream of the weir or in cracks and crevices) where roots can take hold are likely locations for vegetation growth. Over time, large roots may penetrate the structure, providing a route for water to access the structure and promote weathering, and displacing masonry units, creating an uneven crest level or new seepage paths, which may eventually leading to loss of fill material. Trees growing in the weir structure or side walls may fall either naturally or due to wind action creating a large void.

Table 8.8 Maintenance regimes for weirs (after Environment Agency, 2012a, and Canal & River Trust, 2014)

Frequency of activity (number of times per year)	Maintenance regime		
	Low	*Medium*	*High*
Target condition grade	Poor	Fair	Good
Safety inspections	1	1	1
Obstruction removal	-	1	1 to 2
Vegetation clearance	-	0.5 to 1	1 to 2
Sediment management	-	0.2 to 0.5	0.5 to 1
Minor repairs	-	0.5 to 1	1 to 2

Table 8.9 Debris types, sources and risk factors

Debris type	Potential sources	Risk factors
Man-made materials	Fly-tipping, commercial or industrial sites	Vehicle access to channel, urbanisation or social deprivation, restricted access to waste disposal or recycling sites, high winds, flooding, deep or fast flows
Vegetation	Seasonal leaf shedding, decay or breakage, heavy runoff or wind action, erosion of river-banks	Steep or wooded catchment, high winds or heavy rainfall, land management or maintenance regime, climate change
Sediment	Erosion of bed or banks, or collapse of riverside walls, land erosion, landslip or slope failure, catchment changes	Steep catchment, steep or unstable watercourse, land use, agricultural practices, deforestation, climate change

Vegetation with the potential to affect structural integrity should be removed regularly, ideally twice a year, or at least every other year. Woody vegetation with deep roots has the greatest potential to cause damage. Soft vegetation with shallow roots causes less significant damage, but requires management to avoid creating pockets of organic material where woody vegetation can take root.

The method of vegetation clearance depends on the type and size of vegetation, depth of root growth and location (**Table 8.11**). Physical methods are preferable to chemical methods although pulling out deep roots can damage the surface and should be avoided. Using herbicides near water is a last-resort method if others have failed, because they can cause harm the aquatic environment. This method requires consent. Regardless of the method chosen, woody vegetation should be removed in the winter to avoid disturbing breeding birds. Cuttings should be removed from the watercourse to prevent downstream blockage and de-oxygenation of water, as well as the smothering of bankside vegetation.

Sediment management may be considered if it is increasing, the weir function or other infrastructure is at risk, and more sustainable options such as source control are unsuitable. Sediment removal should be undertaken with the advice of an expert geomorphologist. The effects of removal elsewhere are dependent on factors including the supply of material from upstream and sediment continuity to downstream reaches. Consent may be required (see **Section 9.7.2**).

The options for dealing with sediments such as retention, reuse and disposal will be greatly influenced by their physical and chemical properties and the specific circumstances of the site. The deep, slow flow upstream of a weir can lead to the accumulation of sediment, contaminants or material of archaeological interest, depending on the land use upstream. This has implications for sediment and/or weir removal and modification, either due to impacts on water quality, risk of release downstream or disposal of the excavated material. For excavated or dredged materials where contaminant levels are assessed as being acceptable then coarse, free-draining sediments may be required to be reintroduced to the watercourse downstream to minimise its effect on geomorphological conditions or processes. On occasions, it may be used as a secondary aggregate, while fine, water-retaining materials may be used for backfilling, or spreading on land for agricultural or ecological benefit. Minor repairs to keep a weir in the required condition may include operational safety repairs, structural repairs or scour protection works (**Table 8.10**). Repairs are discussed in more detail in **Chapter 14**.

8.4 MONITORING

Monitoring may be required to supplement inspections, to inform maintenance or refurbishment, or to improve knowledge. Monitoring may also be required as a condition of consent to work in watercourses, fish pass approval or impoundment licensing (**Section 8.4**).

Structural or scour monitoring may be required if defects are identified which are progressive, but where remedial action cannot yet be justified. This can indicate the rate of deterioration, improve confidence in a structure and allow intervention at the optimum time. Monitoring may involve regular manual measurements or continuous measurements using telemetry. Some monitoring methods applicable to weirs and sources of further information are given in **Table 8.11**. Sediment monitoring is discussed in **Section 12.5**.

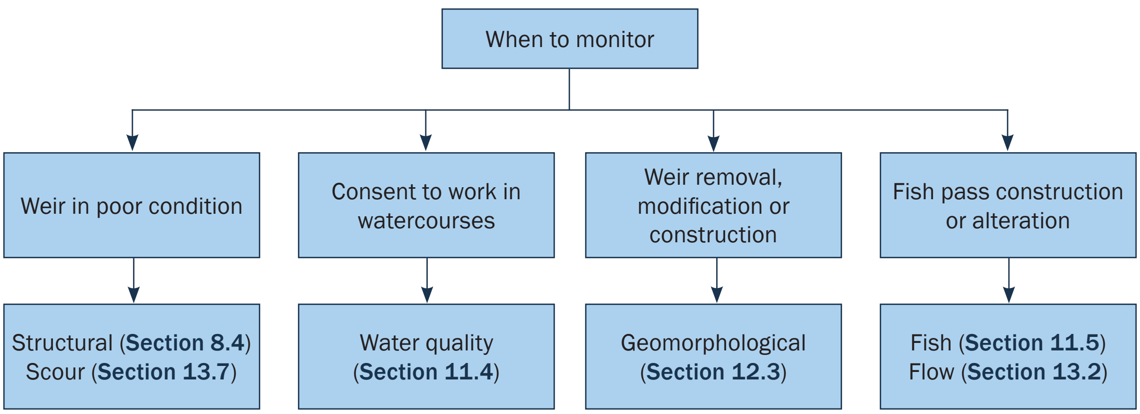

Figure 8.2 *When to monitor*

Table 8.10 Maintenance methods for weirs

Type	Description
Obstruction removal (see Kitchen and Van Leeuwen, in press)	
Remove debris	Provide safe access for removal (eg footbridge, retractable booms, broad weir crest, harness points on side walls, space for lifting equipment adjacent to the weir). Method of removal depends on access, size of debris and risks
Reduce probability of blockage	Install floating booms or surface skimmers upstream, although these must be inspected and maintained Provide open view fencing to avoid creating a visual barrier, encourage community involvement and a sense of ownership
Reduce debris load	Reduce fly-tipping through public awareness campaigns, recycling facilities, routine clearance of the watercourse (subject to negotiation with riparian owners) or enforcement action Reduce refuse from commercial or industrial sites by liaising with site owner to secure material or install physical barrier (provided this does not affect flow capacity or access for maintenance)
Vegetation clearance (see Bentley et al, 2014, and Sowden, 1990)	
Woody vegetation adjacent to weir	Cut back and grind out shallow roots Cut back and treat remaining stump to prevent re-growth, either by drilling holes in the stump and treating with herbicide, or cutting a cross in the top
Woody vegetation within weir structure	Pollard or coppice Remove and dig out roots Remove and install impermeable barrier to prevent flow paths developing along the line of the rotting roots Avoid cutting back to a stump as roots will rot and create new flow paths through the weir
Soft vegetation	Remove manually by weeding or high pressure water jetting Avoid herbicide except for spot treatment Ivy requires a staged removal which takes up to two years
Sediment management (see Environment Agency, 2011a, Forestry Commission, 2011, Defra, 2005, and SEPA, 2008)	
Prevention	Encourage sediment continuity (sediment movement from upstream to downstream), by weir removal, partial removal, lowering, bypassing, or by providing a gradually sloping upstream face, and optimising weir location and alignment within the river Install groynes or deflectors to change flow and deposition patterns. Positioning and size needs to be considered in the context of the river's geomorphological processes
Reduce sediment load	Prepare erosion risk map to identify potential sources of sediment, pathways for sediment movement and the location of potential mitigation measures Control soil erosion in catchment by woodlands or land management Control river-bank erosion (where appropriate, as erosion is in many cases a natural process) by planting riverside trees to provide shade for the river-banks, allow vegetation to grow and protect against erosion. Avoid too much shade which can cause vegetation loss and bank erosion
Sediment removal	Remove sediment and re-introduce downstream to minimise sediment starvation and erosion (may be unsustainable in the long-term) Remove sediment and spread on land for environmental benefit (if nutrient-rich and uncontaminated) Depending on the type of sediment being eliminated: ■ remove geomorphologically-active mobile gravel deposits, but retain bedforms ■ leave a significant proportion of the bar in good condition, preferably the coarse armoured material at the head of a bar ■ leave a buffer zone between the wetted channel and extraction zone ■ avoid removing material below the buffer zone or water level ■ avoid creating abrupt transitions in slope that may lead to knick-point recession.
Minor repairs	
Operational safety repairs	Sign cleaning, inspection and operation of sluices to check function, greasing and cleaning of sluices, tightening bolts, removal of vegetation from edges and cleaning and painting of handrails
Structural repairs (see Sowden, 1990, Cork and Chamberlain, 2015)	Re-pointing, facing or replacement of masonry units, grouting to fill voids to rear of the wall Concrete patch repairs, void filling joint repairs or sealant replacement
Scour (see Kirby *et al*, 2015)	Scour reduction, scour protection or structural measures

Table 8.11 When to monitor

Type	When and what to monitor
Structural monitoring (Sowden, 1990)	Weir with defects (eg cracking, surface defects, movement or leakage). Cracking: monitor crack length, width and orientation, using manual measurement of distance between studs, tell tales or strain gauges. Surface damage: monitor extent and depth of damage, using survey and/or fixed point photography. Movement: monitor level, alignment and/or inclination of structure elements (eg weir crest), using level survey, misalignment of crest or water-line, plumb bob, tilt sensors or accelerometers. Leakage: monitor weep holes, location and leakage rate.
Scour monitoring (Kirby *et al*, 2015)	To determine maximum scour depth, reduce public safety risk or minimise disruption. Maximum scour depth can be measured by physical probing, soundings, magnetic sliding collar or float-out devices. Scour development over time can be monitored using buried or driven rods, sonar or geophysical methods. Monitor structural movement using a tiltmeter and/or accelerometer.
Water quality monitoring (**Section 11.4**)	Condition of consent for work in watercourses. Determine sediment composition and presence of contaminants before weir removal, particularly fines, which can cause turbidity and smother habitat. Monitor turbidity during or after modification works to ensure the effectiveness of measures to control silt.
Fish monitoring (**Section 11.5**)	Condition of fish pass approval. Monitor fish species, age and length class after completion, to confirm satisfactory operation of a fish pass over the range of river flows in which migration occurs. This will also help determine the proportion of the target fish species that succeed in ascending the pass, identifies the need for any improvements, and informs future practice in design and construction.
Environmental monitoring (**Section 11.6**)	Condition of abstraction licensing. Monitor fish populations or plant species to ensure that abstraction does not harm the environment.
Geomorphological monitoring (**Section 12.6, Case study A3.4**)	Weir removal, modification or construction. Monitor forms and processes, including impacts on sediment type, size and transport up and downstream, habitat and species response, channel morphology and geometry response, erosion and deposition changes, and flow variability and diversity (hydraulic habitat/biotopes).
Flow monitoring (**Chapter 13**)	Condition of fish pass approval, to check that the flow through the fish pass is sufficient over a range of river conditions. Condition of abstraction licence to show that the scheme was constructed and is being operated as licensed (particularly below hands-off flow).

8.5 ACCESS AND WATER MANAGEMENT

Asset management requires safe access to the weir structure and water management. This can present additional challenges to weir owners due to the need to provide safe access for authorised persons for inspection and maintenance, while discouraging unauthorised access. Measures to facilitate safe access for inspection, debris or sediment management and repairs, including water management, are summarised in **Table 8.12**.

Operational safety and measures to discourage access from land or water are discussed in **Chapter 10**. More information on water management is given in **Chapter 15**.

Table 8.12 Access and water management measures

Aspect	Measure
Access to weir	■ steps to weir structure ■ bridge over weir structure ■ access to river upstream and downstream of weir ■ slipway upstream and downstream of weir for boatwork ■ harness points on abutments
Weir structure	■ broad crest ■ apron with mild slope and relatively flat toe ■ rough surface to apron, because they can often become slimy once wet
For plant	■ space for lifting equipment adjacent to the weir
For boatwork	■ vertical upstream face to weir to allow a boat to moor against the upstream face for adjustment of dam boards (to control water level on navigations where inflow and lock operations vary with season) (note this conflicts with measures to improve sediment continuity) ■ belay points upstream and downstream of the weir for tethering a boat – ideally positioned diagonally across the river to avoid creating a V-shape in the centre of the river from which the boat cannot be recovered (**Figure 10.10**)
Water management	■ stop logs to allow sections of weir to be dewatered for inspection ■ sluice in or next to the weir to allow temporary drawdown of upstream water levels ■ stop logs at inlet to fish pass or smolt chute to allow de-watering for inspection and maintenance
Debris management	■ space for temporary storage of debris before transport (if removal is the preferred response)

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9 Law and policy

9.1 INTRODUCTION

This chapter summarises the legal and policy framework affecting the design, maintenance, modification and removal of weirs in the UK. It provides information on the legal considerations, but is not intended to be a comprehensive or definitive text and the user is advised to consult a competent legal authority for advice.

The legal framework regarding weirs varies within the UK although there are some common principles. The law confers rights, powers and duties on the owners of weirs and relevant statutory authorities:

- **Rights** – the ability to act or do something, usually conferred as part of land ownership.
- **Powers** – a legal entitlement to do something and is based on statutory legislation. The powers are usually given to a statutory body.
- **Duties** – the requirement to do something (eg apply for a permit or consent), or not to do something (eg cause nuisance or flood a neighbour). A duty can derive from statute or case law.

9.2 GENERAL DUTIES

9.2.1 Ownership

Ownership of weirs can be complex due to unknown or shared ownership, or shared interests. Under common law, on non-tidal rivers, a river-bank owner typically owns the river bed up to the centreline. However, the ownership of some weirs is unknown because the land has not changed hands since compulsory land registration was introduced in 1990 and the land remains unregistered. Title plans may show that weirs have a named but otherwise untraceable owner, three or four owners, or that the river has since been diverted away from the weir. Some weirs are simply 'orphaned' with no known owner, perhaps due to being perceived as a liability.

A weir that fulfils several functions, such as water level management for abstraction, flood risk management or fish passage can have multiple stakeholders. These may range from organisations with significant financial interests such as navigation authorities or power generation companies, to smaller interest groups such as angling or watersports clubs. Responsibility for operation and maintenance can be complex, and modification of a weir may affect the rights of another party (eg by restricting navigation, reducing flow available for abstraction, causing scour or sedimentation, increasing flood risk or obstructing the passage of fish).

A weir owner may need to consult many stakeholders and seek financial contributions before undertaking works. Cursory guidance on the legal issues in England and Wales is given in Ackers *et al* (2009).

9.2.2 Occupiers' liability

The Occupiers Liability Acts of 1957 and 1984 impose a duty of care on occupiers in the UK who have control over premises such as a weir. The occupier must ensure that land is reasonably safe for visitors (including trespassers) who use it for the intended or permitted purposes. The duty of care does not apply to visitors who willingly accept risks, for example, canoeists who accept the risks of their sport, and the duty may be discharged by providing adequate warning to allow the visitor to avoid the hazard. At weirs, this may involve installing visible or audible signs, or physical barriers such as a boom (although it should be noted these can have adverse effects on the ease of self-rescue from the water) (see **Chapter 10** for more information on safety). Occupiers should be aware that any river which is suitable for passage by canoes will be accessed, regardless of the presence or absence of an access agreement.

Natural Resources Wales (NRW, 2000) provides guidance on the Occupiers' Liability Acts in Wales and its links to the Countryside and Rights of Way (CRoW) Act 2000. Scottish Natural Heritage (SNH, 2005) and DOENI (2007) provide short guides to occupiers' legal liabilities in relation to public outdoor access, summarising the law and providing case law relating to fencing or signing of natural hazards.

9.2.3 Nuisance

Nuisance may occur when the action (or inaction) of one landowner causes unreasonable interference with another landholder. So a weir owner may need to maintain a weir, or remove debris or sediment from it to avoid causing flooding, erosion or structural failure to another landowner.

The construction of a weir within a river has the potential to cause nuisance by obstructing navigation, raising water levels or obstructing fish migration to upstream fisheries (eg the case of Weld v Hornby which involved the erection by Hornby of a stone weir across the River Ribble that damaged Weld's fishery upstream, National Archives, 1806).

The public right of navigation remains common law, but the nuisance due to raising water levels or obstructing fish passage is now covered by statute law in the UK (eg Water Resources Act 1991, Salmon and Freshwater Fisheries Act 1975, Salmon and Freshwater Fisheries (Consolidation) (Scotland) Act 2003).

9.3 WATER LEVEL MANAGEMENT

9.3.1 Flood risk management

Flood risk management and land drainage law in the UK governs works to construct or modify structures in, over or under watercourses, or otherwise obstruct flow, including weirs. The aim is to maintain land drainage and the flow of water in watercourses, ensure the passage of fish, and ensure that maintenance of the watercourse is possible.

Guidance on the law in England and Wales is available in Howarth (2002) and ICE (2010). SEPA (2015b) covers engineering works in inland surface waters or wetlands, and defines activities that require a licence under the CAR Regulations.

Directive 2007/60/EC (Floods Directive) aims to improve the management of flooding at catchment scale and covers flooding from the sea, rivers, surface water and reservoirs. The Directive requires the preparation of flood risk management plans setting out objectives and measures for managing flood risk over large areas, the first of which are undergoing consultation in 2015. The Directive also encourages co-ordination with the WFD (**Section 9.4**) and RBMPs to make the most of opportunities to deliver multiple benefits, streamline delivery, or to co-ordinate monitoring and stakeholder engagement. As an example, weir removal may reduce flood risk, but may also deliver sediment continuity improvements, which meet both flooding and WFD objectives.

The Water Resources Act 1991 gives the Environment Agency and NRW powers on main rivers in England and Wales. Main rivers are defined in Section 113(1) of the Act and are listed on the Environment Agency website or identified by contacting the Environment Agency or NRW (see **Websites**). The Act and associated byelaws require flood defence consent for works in, over, under or near to main rivers to ensure that such activities do not cause flooding or make an existing flooding problem worse, and do not adversely affect the local environment, fisheries, wildlife or flood defences. Local byelaws also govern the distance between development and a watercourse to provide a margin for maintenance.

It should be noted that flood defence consents in England and Wales now come under the Environmental Permitting (England and Wales) (Amendment) Regulations 2016. The term flood defence consent has been superseded by flood risk activity permits.

An 'ordinary' watercourse includes all other watercourses, for which the LA or IDB has powers with regard to flood defence. Areas covered by IDBs can be seen on the Association of Drainage Authorities (ADA) website (see **Websites**). Under Section 23 of the Land Drainage Act 1991, ordinary watercourse consent is required for construction on ordinary watercourses. Enforcement of this now lies with LLFA's under the Flood and Water Management Act 2010. This Act empowers the Environment Agency, NRW, LAs and IDBs to designate structures (such as weirs) that are believed to affect flood risk as 'flood management assets' and to require the owners of those structures to seek consent for their removal or modification. If an obstruction (such as a weir) is erected, raised or otherwise altered causing a nuisance, the Land Drainage Act 1991 allows the relevant authority to serve notice requiring abatement of the nuisance.

Websites

Association of Drainage Authorities: **www.ada.org.uk**

Environment Agency: **http://apps.environment-agency.gov.uk/wiyby/151293.aspx**

The Flood Risk Management (Scotland) Act 2009 imposes a general duty to manage flood risk in a sustainable way and contribute to sustainable development, promoting a move towards restoring river channels to a more natural form and away from new structures unless in exceptional situations. SEPA has a duty to map and assess artificial structures and natural features with the potential to affect flood risk or the transport and deposition of sediment, such as weirs. Section 18 of this Act requires LAs to assess bodies of water for flood risk and to prepare a schedule of clearance work and Section 59 provides a duty on LAs to carry out works to reduce flood risk although there is no provision for the recovery of costs from owners.

In Northern Ireland, the failure of occupiers (land owners) to maintain the efficiency of watercourses that run on or through, or bound their land is dealt with by Schedule 5 of the Drainage (Northern Ireland) Order 1973. Rivers Agency consent is required for works adjacent to or affecting a watercourse (such as weirs) if the work is likely to affect the flow of water in the watercourse, impede any drainage work, prevent or impede the passage of fish, or interfere with, or in any way hinder, the maintenance of the watercourse. The Rivers Agency may serve notice requiring the occupier to scour out or cleanse the watercourse, which would include removing an unconsented weir or removal of debris. If this fails, the Agency may undertake the work and recover expenses, as well as impose a fine.

9.3.2 Hydropower

The use or construction of weirs for hydropower is covered by policies, position statements or guidance notes provided by the regulatory authorities.

General principles are:

- Every proposal is unique and will be considered on its own merits.
- Choose sites carefully and follow guidance.
- Make protecting the environment a priority within the scheme design and budget.
- Understand that proposals in sites of high environmental sensitivity for new weirs are unlikely to be given consent.

Items to be considered (this is not an exhaustive list) include:

- Avoiding sites and designs that require building new impounding weirs.
- Use turbines that present least harm to fish/ eels and/or provide 'fish protection' screening.

Ensure safe passage for fish where appropriate, eg:

- Protect upstream fish passage by constructing a fish and/or eel pass where fish or eel passage is, or likely to be, impeded.
- Protect downstream fish passage by providing a suitable plunge pool.
- Make provision at flow splits to guide fish along the main channel or to the fish pass.
- In some circumstances, provide a screen on the diversion structure (unless the hydropower scheme uses an Archimedian screw and has no screen on the tailrace).
- Maintain sufficient flow, depth and width to support ecology, fisheries and amenity in the depleted reach between the abstraction and discharge points.
- Maintain sufficient water depth for navigation, where appropriate.
- Seek hydropower design that avoids impairing flood management structures, adversely affecting land drainage or increasing flood risk.
- Avoid further disrupting, or preventing the restoration of, longitudinal connectivity (the natural movement of sediment, animals or organic matter through the channel network).

9.3.3 Navigation

Navigation law has implications for the maintenance of navigations and the provision of access around weirs.

In the UK and Ireland, there is a common law public right of navigation on navigable tidal watercourses. On other watercourses, navigation law is unclear (except in Scotland where river users have a longstanding right of access under the Land Reform (Scotland) Act 2003). Some argue that there is no automatic right of public navigation unless the watercourse is dedicated for public use, while others attest that the Magna Carta provides for a common law right of access along all rivers that are physically navigable. Differing summaries of public rights of navigation are available in Church *et al* (2001) and on the British Canoeing and Canoeing Ireland websites (see **Websites**).

Websites
British Canoeing: **www.britishcanoeing.org.uk**
Canoeing Ireland: **http://canoe.ie**

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The CRoW Act 2000 may provide access up to or over water, but does not extend to bathing, fishing or boating.

Navigation authority consent is generally required before doing anything that obstructs or interferes with navigation. The Canal & River Trust and Scottish Canals (both formerly British Waterways) have powers under the British Waterways Act 1988 to stop, divert or interfere with rights of way during works, subject to obtaining consent for interference with rivers, waterways or navigations. There are other organisations, including the Environment Agency, which have responsibility for navigation on some watercourses in England. Those navigation authorities operate under separate Acts, Regulations or bylaws, for example the Thames Conservancy Acts (1932–1972). Similar powers exist for Waterways Ireland, which administers navigation on the Lower Bann and Erne system in Northern Ireland (see **Websites**).

Websites
Waterways Ireland: **www.waterwaysireland.org**

9.4 ENVIRONMENT

9.4.1 General duties

General duties impose a requirement on public and other bodies to consider additional factors such as biodiversity or recreation when undertaking their primary functions. This has implications for works affecting weirs and requires multiple objectives to be considered.

Public bodies in the UK have a duty to conserve and enhance biodiversity, providing it is consistent with the exercise of their functions, under the Natural Environment and Rural Communities (NERC) Act 2006 in England and Wales, Nature Conservation (Scotland) Act 2004 and Wildlife and Natural Environment Act (Northern Ireland) 2011. The duty aims to raise the profile of biodiversity and to make it an integral part of policy and decision making.

The CRoW Act 2000 requires relevant authorities (any Minister of the Crown, public body, statutory undertaker or person holding public office in England and Wales) to have regard to conserving and enhancing the natural environment of the Area of Outstanding Natural Beauty (AONB) when carrying out their duties.

The Environment Agency has a duty to:

- promote the conservation and enhancement of the natural beauty and amenity of inland waters and the land associated with such waters
- conserve flora and fauna that are dependent on an aquatic environment and the use of such waters and land for recreational purposes
- take into account the needs of persons who are chronically sick or disabled (Environment Act 1995).

NRW has a duty to *"exercise its functions so as to further nature conservation and the conservation and enhancement of natural beauty and amenity"* under the Natural Resources Body for Wales (Functions) Order 2013. Duties include:

- promoting access to, and enjoyment of, the outdoors and natural environment
- protecting and conserving sites, buildings and objects of archaeological, architectural, engineering or historic interest, and maintaining public access to them
- ensuring that water or land is available for recreation.

LLFAs, district councils and IDBs in England and Wales are required to aim to contribute towards sustainable development when discharging their flood risk management functions, under the Flood and Water Management Act 2010.

SEPA monitors and reports on the condition of Scotland's environment and considers that its primary role is to protect and improve the environment.

DOENI has a duty to promote the conservation of water resources and the cleanliness of water in waterways and underground strata (The Water (Northern Ireland) Order 1999). In performing its duty, the DOENI must have regard to the:

- needs of industry and agriculture
- protection of fisheries and public health
- preservation of amenity
- conservation of flora, fauna, geological or physiographical features of special interest and any feature of archaeological, historical, architectural or traditional interest.

The Canal & River Trust and Scottish Canals have a duty to take reasonable steps to conserve flora, fauna, geophysical or physiographical features of scientific interest in exercising their powers under

the British Waterways Act 1988. Waterways Ireland has similar duties in Northern Ireland.

9.4.2 Water Framework Directive (WFD)

Directive 2000/60/EC (Water Framework Directive) is applicable to weirs, and guidance on its implications for weirs is given in Elbourne *et al* (2013) and in an online WFD mitigation measures manual (Environment Agency, 2013d).

The WFD and delegated legislation aims to maintain or improve the chemical and ecological status of watercourses and to restore surface waters to a more natural state where technically feasible. This is in order to protect human health, water supply, natural ecosystems and biodiversity. The WFD requires member states of the European Union (EU) to achieve good status (or potential for heavily modified or artificial waterbodies) for waterbodies in terms of 30 different parameters including chemical status, biological elements (fish, aquatic insects and plants), physical-chemical elements (phosphate, nutrients and dissolved oxygen), specific pollutants (heavy metals and organic compounds) and hydro-morphology (depth, width, flow and structure).

This means that river flows, water levels and sediment transport are important measures of a waterbody's status. The removal of obstructions such as weirs to improve longitudinal connectivity (and sediment transport), the ability of a watercourse to erode its bed and banks, and fish passage, is encouraged and is required where it is an impediment to fish migration. Conversely, it is not acceptable for a new weir to result in deterioration of the status of a waterbody.

Under the WFD, RBMPs are prepared to identify discrepancies between existing and required status, and provide a programme of measures to meet environmental objectives of the WFD. These must be updated every six years and are co-ordinated by the Environment Agency, NRW, SEPA and NIEA as the relevant regulatory authorities in the UK. An applicant applying for a consent or licence to undertake physical works in or around a river may be required to provide the relevant authority with information to demonstrate the proposed works meet the requirements of the WFD and wider environmental legislation (see **Section 9.7**).

9.4.3 Water quality

The Water Resources Act 1991 and the Water (Northern Ireland) Order 1999 prohibit causing or knowingly permitting polluting matter or solid waste to enter surface water or groundwater.

In Scotland, the Water Environment (Controlled Activities) (Scotland) Regulations (CAR) 2011 aim to protect the water environment and regulate pollution control, abstraction, impoundment and engineering works in or near inland waters or wetlands. Some activities are allowed under the general binding rules, but others require authorisation from SEPA. Guidance is given in SEPA (2015b).

9.4.4 Habitats and protected species

Council Directive 92/43/EEC (Habitats Directive) and delegated legislation aim to conserve internationally important natural habitats, and species of flora and fauna listed in the annexes of the Directive. The Directive sets requirements for plans and projects likely to affect designated Special Protection Areas (SPAs) and Special Areas of Conservation (SACs), known as Natura 2000 sites (or European sites in the UK). Under UK policy, proposed and candidate SPAs and SACs, and Ramsar sites are also given the same protection.

The construction of weirs may have a role in diverting water or maintaining water levels in order to support designated wetlands and to create new habitat. The removal, modification or construction of a weir may affect protected species, such as otter, bats, white-clawed crayfish, salmon, lamprey, shad or freshwater pearl mussel. Works should avoid disturbing the animal, damaging or blocking access to its habitat, but if this is not possible, then mitigation measures and a licence will be required. Works that are likely to affect a European site (including proposed works outside the site boundary) require an appropriate assessment to establish whether there may be adverse effects on the site, which is distinct from an EIA although some areas may overlap. As a rule, the impact of any work on the environment should be minimised. Advice on the consents required can be obtained from Natural England, NRW, SNH or NIEA.

9.4.5 Invasive non-native species

Invasive non-native species (INNS) are plants or animals that have been introduced to the UK and have the potential to spread and cause significant adverse effect on biodiversity, environment, economy or social interests. Works to weirs or watercourses have the potential to spread INNS to other parts of the river system. Examples of INNS include Japanese knotweed, giant hogweed, signal crayfish and floating pennywort. The Infrastructure Act 2015 gives powers to environmental authorities to compel landowners to take action, or to enter land to take action on INNS. This supplements the Wildlife and Countryside Act 1981, which prohibits the sale of INNS, or any materials from which they can be reproduced or propagated. The presence of INNS should be determined before any works in watercourses are started.

Further information is available from the Great Britain non-native species secretariat (NNSS) (see **Websites**) and in Booy *et al* (2008).

Websites

Great Britain non-native species secretariat:
www.nonnativespecies.org/home/index.cfm

9.4.6 Fish and eel passage

Under UK law, it is an offence to obstruct the passage of salmon, migratory trout or eels, to cause direct mortality to any fish, to cause the degradation of habitats and to allow any deleterious matter (eg silt, sand) to enter a river or watercourse (except under licence). The law relating to fisheries is primarily governed by the Salmon and Freshwater Fisheries Act 1975 and the Fisheries Act (Northern Ireland) 1966, although the WFD is also influential.

There is a duty to minimise disruption to fish passage during construction or maintenance, to meet water quality standards for suspended solids (among other things) in salmonid and shellfish waters, and to provide and maintain a fish pass to assist fish passage at all times. This necessitates the provision of fish passes for salmon or migratory trout when constructing new weirs, raising or altering existing weirs, or rebuilding or reinstating weirs that have been destroyed or taken down to the extent of half of its length.

Council Directive No 1100/2007 (the Eel Regulations) and delegated legislation aims to recover eel stocks by targeting causes of mortality in eels. This legislation requires the construction of eel passes at obstructions such as weirs (including temporary ones) to allow upstream migration, eel screens to prevent harm or a by-wash to allow downstream passage of eels. It is prohibited to damage or interfere with an eel screen, or do anything that may obstruct or impede the passage of eels through an eel pass or by-wash.

Guidance on the law relating to fisheries and eels is given in Armstrong *et al* (2010). Environment Agency (2011b) describes the implementation of powers granted under the Eels (England and Wales) Regulations 2009. In Scotland, SEPA policies on fish and eel passage are embedded within their guidance on run-of-river hydropower (SEPA, 2015b).

In England, government policy on managing freshwater fisheries sets out a proposal to introduce new legislation to fish migration of all fish species (Defra, 2016). This will give the Environment Agency greater powers to install fish passes and allow for the removal of obstructions and installation of fish screens to stop fish entering water intake channels.

9.4.7 Heritage

Weirs that are designated heritage assets such as Scheduled Monuments, listed buildings or that fall within wider designations such as registered parks and gardens, World Heritage Sites (WHS) or Conservation Areas, benefit from some legal protection. Relevant statutes are the Ancient Monuments and Archaeological Areas Act 1979, Civic Amenities Act 1967, Historic Buildings and Ancient Monuments Act 1953, Historic Monuments and Archaeological Objects (Northern Ireland) Order 1995, Planning (Listed Buildings and Conservation Areas) Act 1990, Planning (Listed Buildings and Conservation Areas) (Scotland) Act 1997 and Planning (Northern Ireland) Order 1991.

If a weir or its surroundings are designated heritage assets, the National Planning Policy Framework (NPPF) states that significance can be harmed by alteration to it or development in its setting. Any harm to significance requires "clear and convincing justification" and "substantial harm or loss" should be exceptional, or in the case of the highest level of designations "wholly exceptional" (DCLG, 2012). This applies to activities requiring planning consent, but good

practice should apply these policies where planning consent is not required. Specific consents are required for works that affect listed buildings, Scheduled Monuments or Conservation Areas (see **Section 11.8.4**). Any works must be sympathetic to the heritage significance of the structure and its context, and it is likely that a programme of archaeological recording and mitigation would be required.

Designated heritage assets can be identified by consulting Historic England, Cadw, Historic Environment Scotland or NIEA (Sites and Monuments Records). The National Heritage List for England (NHLE) is the official and up-to-date database of nationally designated heritage assets (see **Websites**). LAs may also hold locally listed buildings that do not have national designated status, but are held as locally important heritage assets. These will be identified by the relevant LA rather than the NHLE.

It should be noted that even undesignated heritage assets have a status under planning guidance that may require consideration. Also, development in the setting of a heritage asset, and not just alteration to it, may harm its significance. To allow informed planning decisions to be made, it is important that a statement of significance is prepared and, as a minimum, the relevant Historic Environment Record (HER) is consulted and the heritage assets assessed using appropriate expertise.

Listed building consent is required for works to listed buildings and the consent conditions may restrict the choice of materials or finishes. It is an offence to demolish, alter or extend a listed building without authorisation and failure to comply is a criminal offence. The works need not enhance the character or appearance of the area, but must not harm it. Listed building consent is obtained from the LPA who may consult the national heritage body (English Heritage, Historic Environment Scotland, CADW or NIEA).

LAs are required to prepare a development plan for each Conservation Area. It is worthwhile consulting this when planning works as the impact of demolition on the area (and also the setting of a heritage asset) is a material consideration in determining an application for planning permission.

Scheduled Monument consent is required from the relevant national Secretary of State (SoS) for any works resulting in demolition, destruction or damage, or the flooding of land in, on or under which there is a Scheduled Monument. This has implications for works to weirs which raise water levels.

WHS are places listed by UNESCO (the United Nations Educational, Scientific and Cultural Organization) as of special cultural or physical significance. In the UK, there are 28 and at least four of those include weirs (Pulteney Weir at Bath, Fountains Abbey and Studley Royal, Saltaire, Derwent Valley Mills) (see **Websites**).

Websites

National Heritage List of England: **www.historicengland.org.uk/listing/the-list**

UNESCO: **http://whc.unesco.org/en/list**

In England, the National Heritage Protection Plan (NHPP) provides a framework for heritage protection, with the aim of encouraging a wide variety of organisations to develop action plans (English Heritage, 2011a). English Heritage (2011b) sets out the contribution that Historic England (responsible for the listing, planning, grants or heritage research and advice functions of English Heritage from April 2015) would make to support the objectives of the framework. The action plan recommended a pilot assessment of character, value and significance of weirs in partnership with the Environment Agency.

Heathcote (2012) notes that weirs are increasingly under threat from development (for hydropower generation), replacement or demolition (to improve the ecological status of rivers by removing barriers to fish and eel passage).

The Canal & River Trust (2012a) and Scottish Canals (2013–2038) set out general principles applying to the management of historic canal assets. They seek to manage the physical impact of human activities in order to protect waterway heritage and to ensure that every addition and alteration to its historic structures is carefully judged, balancing safety, cost, historical integrity, use, aesthetics and other needs. Both organisations aim to give all heritage assets, whether designated or non-designated, the same level of beneficial treatment and, where possible, to perform regular maintenance to significant heritage assets in order to prolong lifespan and reduce future repair costs. Specific principles include taking an approach based on minimum physical intervention, using reversible interventions where possible, and giving primacy to safety in all work.

9.4.8 Landscape and visual amenity

The National Parks and Access to the Countryside Act 1949, and Section 17A of the Norfolk and Suffolk Broads Act 1988 impose duties on public bodies and statutory undertakers to conserve and enhance the natural beauty, wildlife and cultural heritage of National Parks. Other duties include conserving and enhancing the natural beauty of the Norfolk Broads, promote enjoyment by the public and protect the interests of navigation of them.

As noted in **Section 9.4.1**, various legislation promote the duty on public bodies to have regard to conserving and enhancing the natural beauty and amenity in relation to, for example, AONB under the CRoW Act 2000, and the duties imposed on the Environment Agency under the Environment Act 1995 and the Water Act 2003. In addition, the Natural Resources Body for Wales (Functions) Order 2013 imposes wide-ranging requirements with respect to the protection and enhancement of established amenity and recreation in the water environment.

Tree and hedgerow removal may require consent in Conservation Areas, if the trees are protected by Tree Preservation Orders (TPO) under the Town and Country Planning Act 1990 and if hedgerows fall under the Hedgerow Regulations 1997. If planning permission is granted, these requirements are superseded, but should inform the decision making process for the design of the works.

9.4.9 Sediment and waste material

Waste management law has implications for the use or disposal of sediment, vegetation or refuse removed during weir removal, maintenance or modification.

The WFD and delegated legislation aim to protect human health and the environment by preventing or reducing the adverse impacts of waste. This has implications for the removal of material from watercourses, for example, during weir removal or repair. Excavated material or dredgings that require treatment before reuse are classed as waste. Uncontaminated soil or naturally occurring material that has been excavated specifically for construction purposes, or dredgings that will be reused on the same site or watercourse that are proved to be non-hazardous, may not be classed as waste. The WFD defines a waste hierarchy, prevention, reuse, recycle, recovery and disposal, and requires measures to ensure that waste does not endanger human health, harm the environment, cause nuisance, or adversely affect the countryside or places of special interest.

In the UK, some activities involving dredgings are exempt from waste licensing, but must be registered with the Environment Agency, NRW, SEPA or the NIEA. The relevant regulations are the Environmental Permitting (England and Wales) (Amendment) Regulations 2016 and the Waste Management Licensing (Scotland) Regulations 2011. In England and Wales, the dredging of materials from inland waterways falls under the Controlled Waste (England and Wales) Regulations 2012. A useful summary of the legislative controls affecting the dredging of sediments from inland waterways is provided in AINA (2013).

Should it be proposed to reuse site-derived materials (including dredged materials such as sediments), these activities may potentially fall under the Environmental Permitting (England and Wales) Regulations (Amendment) 2016. It is possible to obtain an exemption from these Regulations as set out within paragraph D1, which allow for deposition of dredgings on the banks of the watercourse from which they were removed and for the removal of water. The types of wastes that can be deposited are restricted to include those that fall under EU Waste Code 17 05 06. In addition, a number of other conditions are required to be satisfied in order to obtain an exemption:

- Activities are limited to clearing silt from sections of a river and depositing the dredgings on the banks of the river.
- Activities are also limited to clearing silt and plant matter from sections of a canal, followed by screening to remove litter and deposition to let water drain away. The dredgings are then taken away for spreading on land under an environmental permit.

Activities that are not permitted include deposition on a different watercourse, or deposition from other waters, deposition of hazardous wastes and treatment other than screening or removal of water. The D1 exemption also places an annual limit on the volume of material that can be deposited to up to 50 m^3 per metre length of land along which it is deposited (Environment Agency, 2014c).

9.4.10 Contaminated sediment

Sediment may be contaminated due to historic land use and Council Directive 1999/34/EEC (Landfill Directive) covers the disposal of contaminated waste to landfill. The Directive and delegated legislation prohibits the disposal of certain waste types to landfill, requires the waste producer to ensure that basic characterisation of the waste has taken place and requires treatment of waste before disposal to landfill.

Guidance on dealing with potentially contaminated sediments is available from CL:AIRE (2011). This COP was originally developed to manage wastes arising from greenfield and brownfield sites and is supported by Environment Agency (2013c), which states: *"If materials are dealt with in accordance with the code of practice we consider that those materials are unlikely to be waste at the point when they are to be used for the purpose of land development"*. The COP was amended to include 'soil and mineral-based' dredged materials, with the proviso that: *"dredged material will not be considered as suitable for use until the appropriate amount of dewatering has taken place and is a waste. The dredged material can subsequently be put to use in earthworks as a non-waste once it is confirmed that it will not need to undergo any further treatment"*.

Under the COP, such materials should not be a waste if they are retained on the site provided the reuse is 'certain', they "are suitable for use without any treatment" and "only the quantity necessary for the specified works". Such works can be undertaken under self-regulation so long as the protocols in the COP are followed.

For off-site disposal of materials in the UK, there is a legal requirement to treat contaminated soils before disposal to landfill. To qualify as 'treatment' a three point test must be satisfied as follows:

- It must be a physical, thermal, chemical or biological process including sorting.
- It must change the characteristics of the waste.
- It must do so to reduce its volume or hazardous nature, facilitate handling or enhance recovery.

9.4.11 Environmental damage

The Environmental Damage (Prevention and Remediation) Regulations 2009 implement Directive 2004/35/CE (Environmental Liability Directive). They are based on the 'polluter pays principle' so those responsible prevent and remedy environmental damage, rather than the taxpayer paying. 'Environmental damage' has a specific meaning in the Regulations, covering only the most serious cases. Owners of weirs are required to proactively put in place appropriate pollution prevention measures so that imminent threats and damage does not arise and identifying when there is an imminent threat or actual damage and taking immediate action.

Defra and WAG (2009), Scottish Government (2009) and Environmental Protection Agency (EPA) (2001) have produced guidance to the Regulations as enacted in the UK.

9.5 HEALTH AND SAFETY

Health and safety law applicable to the design, operation, maintenance, modification and removal of river weirs imposes a duty of care on owners and managers to safeguard visitors, and on employers to ensure the safety, health and welfare of workers during design, construction, operation, maintenance, repair or demolition. This is particularly important for weirs where the hazards are often not appreciated by the public. **Chapter 10** also covers health and safety in the context of weir design, removal, operation, and maintenance.

Directive 92/57/EEC aims to ensure that health and safety is treated as an intrinsic part of project development by imposing duties on all parties involved in the planning and management of construction work. The Directive is transposed into national law by the Construction (Design and Management) Regulations (CDM) 2015, which apply to all construction projects, including site investigation, the design and construction of new structures, the maintenance, repair or demolition of existing structures (but excluding routine maintenance), and temporary or mobile construction sites.

The general principles of prevention are to avoid risks where possible, evaluate risks that cannot be avoided and to put in place proportionate measures to control them at source, giving regard to the safety of the public as well as operatives working on site. This means taking reasonable steps to eliminate the hazards associated with weirs, consider safe access for inspection and maintenance, and provide sufficient information

about residual risks. New regulations came into force in England, Wales and Scotland in April 2015 and later introducted in Northern Ireland in August 2015. The new regulations change the duty holders and thresholds for notification.

The Health and Safety at Work etc. Act 1974 in the UK and the Health and Safety at work (Northern Ireland) Order 1978 aim to protect the safety, health and welfare of workers, as well as others affected by the action of those at work. The law imposes duties on employers towards employees and members of the public, and on employees to themselves and to each other. An employer must take 'reasonably practicable' measures to avoid or reduce risk, although both the assessment of risk and what reasonably practicable measures might comprise can be the subject of some debate.

In England and Wales, where visitors or other people suffer an injury or death as a result of a risk or a danger due to the state of the land, the occupier of that land may be liable for those injuries under the Occupiers' Liability Acts 1957 and 1984 (see **Section 9.2.2**).

Finally, the Corporate Manslaughter and Corporate Homicide Act 2007 states that an organisation involved in managing an asset or design or construction work may be guilty of corporate manslaughter (or corporate homicide in Scotland) if its activities are managed or organised in such a way that causes a person's death and amounts to a gross breach of a relevant duty of care owed by the organisation to the deceased.

HSE (2006) summarises health and safety law in the construction industry and provides guidance on identifying hazards and controlling risks on construction sites. Readers should note that the information on CDM is out of date. HSE (2015) provides guidance on the legal requirements of CDM 2015.

9.6 PLANNING POLICY

National planning policies and associated local plans have the potential to affect the design, modification or removal of weirs, by influencing the approach of planners and developers to safety, environment, heritage, recreation or other needs. In the UK, relevant policies are available for England (DCLG, 2012), Wales (WAG, 2016), Scotland (Scottish Government, 2014) and Northern Ireland (DOENI, 2015).

Policies generally aim to contribute to sustainable development and those with the potential to affect weirs include:

- Promote health by protecting and enhancing public rights of way, providing access to open spaces, opportunities for sport and recreation, and better facilities for users.
- Meet the challenge of climate change, flooding and coastal change by increasing the use and supply of renewable and low carbon energy (eg hydropower).
- Conserve and enhance the natural and historic environment.

At river basin scale, flood risk management plans and RBMPs prepared in accordance with the WFD and the Floods Directive also contain objectives and measures to reduce flood risk and achieve good status for watercourses. These may include the removal or management of weirs to eliminate barriers to fish and eel passage and restore longitudinal continuity (sediment transport, fish and mammal passage).

9.7 CONSENT REQUIREMENTS

9.7.1 Consent for work in watercourses

Construction or maintenance work in or near watercourses may require consent and separate consent is required for permanent and temporary works. Additional consents may be required if the weir is or is close to a heritage structure (**Section 11.8**) or is in or near to a designated environmental site (**Section 6.3**).

Guidance on consents for work in watercourses is available in Environment Agency (2014a), SEPA (2015a) and DOENI (2013).

In England and Wales, traditionally a flood defence consent was required from the Environment Agency or NRW for works on, over, under or near a main river, flood or sea defence. For work on other watercourses, ordinary watercourse consent was required from the LLFA or IDB, depending on which body has jurisdiction. Since April 2016 in England and Wales, flood defence consents have been replaced by flood risk activity permits under the Environmental Permitting Regulations 2016.

Under the new permitting regime, there are a number of low-risk activities that are set out in law as excluded or exempt from the Regulations. The Environment Agency and NRW also have the facility to put in place standard rules permitting arrangements for some activities that can be generically dealt with. All other permits will be treated as bespoke and will require some form of flood or environmental assessment. The construction or replacement of a weir is likely to require a bespoke permit under the new regime, however some minor maintenance activities to weirs may be carried out under an exemption or exclusion.

An application for flood defence or ordinary watercourse consent may need to be accompanied by an environmental appraisal and/or a WFD assessment and applicants are advised to seek advice from the LLFA before submitting an application. An environmental appraisal should identify all likely effects of the proposed works on the environment and any measures required to mitigate for those effects. A WFD assessment must consider the impact of the proposed works on the biological, chemical, morphological, and flow aspects of a waterbody, either in the short-term or in the future. The aim is to establish that all new modifications, and certain existing ones, do not contribute to a deterioration in status (or potential status, for artificial or heavily modified waterbodies), and do not prevent the achievement of the target status set for a waterbody in the local RBMP. Guidance on WFD assessment is given by Environment Agency (2016).

In Scotland, a CAR licence is required from SEPA for any activity that directly or indirectly has or is likely to have a significant adverse effect on inland surface waters. Under the general binding rules, the removal of sediment close to a structure requires authorisation, but the maintenance of existing structures and removal or management of debris or trash do not. Operators are permitted to maintain existing engineering works if the footprint and materials remain the same and there is minimal impact on the watercourse (SEPA, 2015b).

In Northern Ireland, consent requirements are set out in DOENI (2013):

- works to or in any watercourse (Rivers Agency)/Department of Culture, Arts and Leisure (DCAL), or if in Foyle and Carlingford areas (Loughs Agency)
- works in tidal watercourses or at coastal locations (DOE Marine Division)
- abstracting or impounding (NIEA – Water Management Unit)
- dredging in the Foyle and Carlingford areas (Loughs Agency)
- planning permission for activities that redirect water flow including the construction of weirs, if required (Planning Northern Ireland)
- extraction of minerals from the sea (an EIA may also be required) (Planning Northern Ireland)
- works in or on the Lower Bann, Erne System, Ulster Canal or Shannon Erne Waterway (Waterways Ireland).

Fisheries protection and management are the remit of both the Loughs Agency, which covers the Foyle and Carlingford areas and the DCAL Inland Fisheries Group, which covers the remainder of Northern Ireland.

9.7.2 Abstraction or impoundment licence

An abstraction or impoundment licence is required to abstract water from inland waters or to impound or obstruct flow in inland waters, for example, by constructing a weir.

Guidance is provided by the regulatory authorities. Environment Agency (2008) covers licencing in England while NRW provides online guidance for Wales (see **Websites**). An impoundment licence application is assessed and conditions may be imposed requiring construction of an eel pass. Navigation authorities benefit from fewer restrictions on abstraction and impounding works. SEPA (2015a) provides guidance for Scotland.

Under the CAR Regulations, general binding rules permit the operation of existing passive weirs which are less than one metre in height and do not affect the passage of salmon or sea trout. The rules also permit abstraction up to 10 m^3 per day. Activities that comply with the general binding rules are treated as compliant with an authorisation under CAR and there is no need to contact SEPA or apply for formal authorisation. Fixed weirs and existing movable weirs that are less than or equal to one metre in height are covered by a simple licence. Other weirs require a complex licence.

NIEA (2010) sets out the types of licence available, the application process, the authorisation process and the criteria used in the determination of a licence in Northern Ireland.

9.7.3 Fish pass approval

The design and installation of a fish or eel pass at a weir requires fish pass approval from the Environment Agency in England or NRW (see NRW, 2014a). As part of the impoundment and/or abstraction licensing, there may be a requirement to provide for future installation of a fish pass, even if a fish pass is not a requirement of the current scheme, by ensuring that suitable space for a fish pass is safeguarded and sufficient flow is reserved for its future operation. Guidance on fish pass approval is available from Armstrong *et al* (2010).

In Scotland, weir management works that affect fish passage require registration or licencing from SEPA under the CAR Regulations. In Northern Ireland, approval is needed from DCAL. An exemption from this requirement can be issued if the regulatory authority is satisfied that it would be unnecessary or unreasonable to provide a fish pass, due to the nature of the weir, river or the kinds of fish present.

9.7.4 Planning permission

The construction, alteration, repair or removal of weirs, or installation of hydropower, may require planning permission from the planning authority under the relevant planning legislation. This aims to ensure that proposed developments comply with planning policy, which may include requirements to avoid increasing flood risk (either at the development or elsewhere), and to conserve or enhance both the natural and historic environments. Planning permission is additional to consent for work in watercourses (**Section 1.1.1**).

Some works can be undertaken without planning permission under permitted development rights, although permitted development rights may be restricted for listed buildings or in designated areas such as conservation areas or national parks. These works include:

- those by a statutory body to improve, maintain or repair a watercourse or for measuring flow
- repair or maintain a weir in connection with the control and operation of an inland waterway
- spread dredgings on land from navigable waterways.

Works such as bank and bed repairs, where the design and footprint of the structure remains the same, and equivalent materials are used, are regarded as maintenance of an existing structure, but planning permission is generally required for hydropower schemes. Emergency repairs can be completed without planning permission but should be notified to the planning authority with justification as soon as possible.

Guidance on planning permission and permitted development rights in the UK is available from the UK Government planning portal (see **Websites**). Planning authorities (typically the LA or the DOE Planning Service in Northern Ireland, see **Websites**) can advise whether proposed works are permitted development or require planning permission.

An application for planning permission must be accompanied by a flood risk assessment if the proposed works or changes in use are located in flood risk areas or areas with critical drainage problems. It will also be required if the proposed works or changes in use will increase flood vulnerability of the development, or if the proposed works are larger than one hectare. Guidance on the need for, and preparation of, a flood risk assessment is available in DCLG (2012), WAG (2004), Scottish Government (2014) and The Planning Service (2006).

An EIA may be required if the proposed works fall within Schedule 1 of the EIA Regulations, meet the criteria within Schedule 2 or are likely to have significant effects on the environment. An EIA is required for the construction of works on inland waterways with an area exceeding one hectare. The LPA will make a decision on the need for EIA based on the criteria set out in the regulations and it is good practice to obtain a screening opinion from the LA regardless of the size of the development. Guidance on EIA is available from the planning portal (see **Websites**) or in SNH (2013). The LPA may require information to demonstrate that the proposed works meet the requirements of the WFD.

Websites

Natural Resources Wales: **naturalresourceswales.gov.uk**

UK Government planning portal: **www.planningportal.gov.uk**

9.7.5 Work affecting heritage assets

Weirs can have significance as heritage assets – both alone or as part of the wider landscape (see **Section 11.8**). In preparing proposals for the maintenance, modification or removal of weirs,

the cultural heritage significance of the weir and its surroundings should be considered at an early stage. This will allow potential impacts on the historic environment to be assessed, and inform any decisions that may arise from potential conflicts.

Works affecting Scheduled Monuments, listed buildings or Conservation Areas require specific consents. Works should be sympathetic to the heritage significance of the structure and its context, and a programme of archaeological recording and mitigation is likely to be required. It is important to seek early advice from statutory bodies and the LPA.

Most weirs are not designated, but this does not mean that they are of no heritage value. Many weirs are integral to the setting and legibility of historic structures and landscapes, but have not received statutory protection. The relevant national planning policies should be followed – even where the works do not require planning permission.

The NPPF applies to activities requiring planning permission, but it is good practice to apply these policies even where planning permission is not needed (DCLG, 2012). If a weir or its surroundings are protected as a designated heritage asset, then substantial harm or loss should be exceptional, or in the case of the highest level of designations, wholly exceptional (Para 132). Applicants should describe the significance of any heritage assets affected, including the contribution made by their setting (Paragraph 128). If a site on which development is proposed includes or has the potential to include heritage assets with archaeological interest, LPAs may need a developer to submit an appropriate desk-based assessment and, where necessary, a field evaluation. Finally, in weighing applications that affect directly or indirectly non-designated heritage assets, balanced judgement is required having regard to the scale of any harm or loss and the significance of the heritage asset (Paragraph 135).

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Planning (Listed Buildings and Conservation Areas) (Scotland) Act 1997 (c.9)

Salmon and Freshwater Fisheries Act 1975 (c.51)

Salmon and Freshwater Fisheries (Consolidation) (Scotland) Act 2003 (asp 15)

Thames Conservancy Act 1972 (c.xivi)

Town and Country Planning Act 1990 (c.8)

Water Act 2003 (c.37)

Water Environment and Water Services (Scotland) Act 2003 (asp 3)

Water Resources Act 1991 (c.57)

Wildlife and Countryside Act 1981 (c.69)

Wildlife and Natural Environment Act (Northern Ireland) 2011 (c.15)

Directives

Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora (Habitats Directive)

Directive 92/57/EEC Temporary or mobile construction sites of 24 June 1992 on the implementation of minimum safety and health requirements at temporary or mobile construction sites (eighth individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC)

Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste (Landfill Directive)

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive)

Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage (Environmental Liability Directive)

Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Floods Directive)

Council Regulation (EC) No 1100/2007 of 18 September 2007 establishing measures for the recovery of the stock of European eel (Eel Regulations)

Orders

Drainage (Northern Ireland) Order 1973 (No. 69/NI 1)

Health and Safety at Work (Northern Ireland) Order 1978 (No. 1039/NI 9)

Historic Monuments and Archaeological Objects (Northern Ireland) Order 1995 (No.1625/NI 9)

The Natural Resources Body for Wales (Functions) Order 2013 (No. 755/W.90)

The Planning (Northern Ireland) Order 1991 (No. 1220/NI 11)

The Town and Country Planning (General Permitted Development) Order 1995 (No. 418)

The Town and Country Planning (General Permitted Development) (Scotland) Order 1992 (No. 223)

The Water (Northern Ireland) Order 1999 (No.662/NI 6)

Regulations

Council Regulation (EC) No 1100/2007 of 18 September 2007 establishing measures for the recovery of the stock of European eel (Eel Regulations)

The Confined Spaces Regulations 1997 (No. 1713)

The Construction (Design and Management) Regulations 2015 (CDM 2015)

The Construction (Design and Management) Regulations (Northern Ireland) 2007 (No. 291)

The Controlled Waste (England and Wales) Regulations 2012 (No. 811)

The Eels (England and Wales) Regulations 2009 (No. 3344)

The Environmental Damage (Prevention and Remediation) Regulations 2009 (No. 153)

The Environmental Permitting (England and Wales) (Amendment) Regulations 2016 (No. 475)

The Hedgerow Regulations 1997 (No. 1160)

The Town and Country Planning (Environmental Impact Assessment) Regulations 2011 (No. 1824)

The Water Environment (Controlled Activities) (Scotland) Regulations (CAR) 2011 (No. 209)

The Waste Management Licensing (Scotland) Regulations 2011 (No. 228)

Further reading

NRW (2014b) *Weirs*, Hydropower Guidance Note (HGN) 14, Natural Resources Wales, Cardiff
https://naturalresources.wales/media/2592/hydropower-guidance-note-hgn-14-weirs.pdf

NRW (2014c) *Weir pools*, Hydropower Guidance Note (HGN) 15, Natural Resources Wales, Cardiff
https://naturalresources.wales/media/2594/hydropower-guidance-note-hgn-15-weir-pools.pdf

NRW (2014c) *Rights of access guidance*, Supporting Guidance Note (SGN) 1, Natural Resources Wales, Cardiff
https://www.naturalresources.wales/media/2596/supporting-guidance-note-sgn-1-rights-of-access-guidance-for-abstraction-licences.pdf

Town and Country Planning (Scotland) Act 1997 (c.8)

The Planning (General Permitted Development) Order (Northern Ireland) 2015 (No.70)

10 Operational safety

10.1 INTRODUCTION

This chapter discusses the operational safety of weirs, the hazards due to weirs, methods of risk assessment and how to mitigate the risks, either by design or retrofitting. It does not cover construction safety, which is not within the scope of this guide.

The hazards due to weirs can be hydraulic, physical, chemical or biological. The greatest hydraulic hazard is the strong re-circulating currents downstream that often look harmless because the water surface is relatively flat, and aeration of turbulent flow which reduces buoyancy and suction currents into sluices and by-washes. Weirs, or low-head dams, are known as ‘drowning machines’ in the USA and sadly, weir-related incidents result in one or two deaths per year in the UK. In the USA, 191 people are known to have died at weirs between 1970 and 2010.

Weir owners have a duty of care to authorised, unauthorised and accidental visitors and should manage the safety risks caused by a weir as far upstream and downstream as they have property rights. Beyond this, the weir owner should assess any specific locations where the hazards are known by the owner to result directly from the weir operations, and inform other affected property owners of the known hazards associated with the weir and its operations. Often there are conflicting demands on weirs and their owners, and a weir that meets functional objectives may present a safety hazard and difficult rescue conditions (**Figure 10.3**).

Guidance on risk assessment is given in **Section 10.2**. If the risk posed by a weir is unacceptable, it can be mitigated by eliminating or reducing the hazard, reducing the likelihood of harm or facilitating rescue (**Section 10.3**).

10.2 RISK ASSESSMENT

10.2.1 Overview

A risk assessment should identify the hazards at a weir, the people who may be harmed and likelihood of them coming to harm, and the ease of self or assisted rescue if they get into difficulty. A list of hazards due to weirs is given in **Table 10.1**.

Those affected can be water or land-based, eg operation and maintenance staff, boaters, canoeists, swimmers, anglers and walkers, particularly those affected by alcohol or drugs, and young people who use a weir or sluices for recreation without appreciating the hazard. The groups affected by hazards are not always obvious as recreation activities often take place outside working hours and may be seasonal. The full range of flow and tailwater conditions should be considered as the hazards and ease of rescue may be different under certain conditions.

A risk assessment should be reviewed periodically, with more frequent assessments if there is a serious incident or accident, if there are changes to the site or before works such as design, maintenance, operation and removal.

10.2.2 Hydraulic hazards

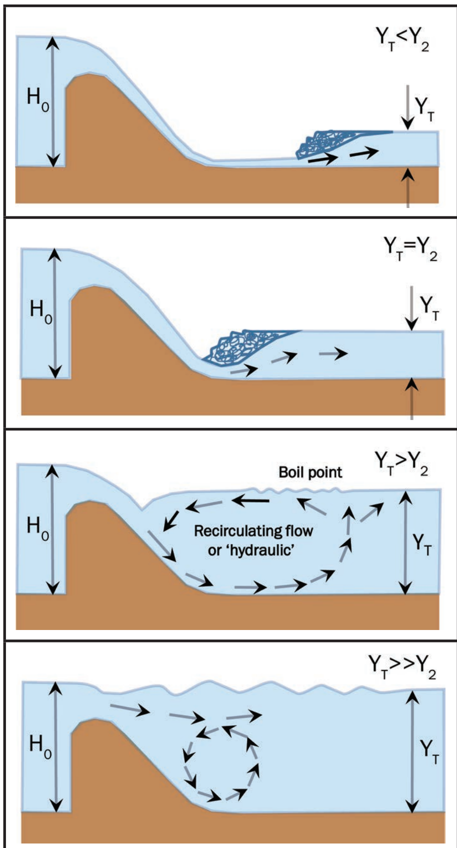
The greatest hazard due to weirs is hydraulic. The recirculating flow (hydraulic jump, hydraulic, stopper, towback or roller) at the base of the weir can prevent a floating object such as a person, dog or canoe from escaping. The person or object is repeatedly dragged underwater at the base of the weir, carried downstream underwater, back to the surface, only to be dragged underwater at the weir toe again, eventually leading to exhaustion and drowning. Aeration of the flow decreases buoyancy, making it hard for the victim to stay afloat.

The hazard depends on the weir flow type and the relationship between tailwater depth and the sequent depth of the hydraulic jump. Four cases can be identified as shown in **Figure 10.1**.

Hydraulic hazards may be determined from photographs of historic flood events or knowledge of the hydraulic behaviour of similar weirs. If this is not possible, then hydraulic assessment, numerical or physical modelling may be required.

Table 10.1 List of hazards due to weirs

Type	Hazard	Consequences
Hydraulic (**Section 10.3.2**)	Deep water downstream of weir	Drowning
	Submerged hydraulic jump at toe of weir (**Figures 10.1 and 10.2**)	Drowning
	Aeration leading to loss of buoyancy	Drowning
	Strong currents, particularly at sluice gates	Drowning
	Strainers and excessive seepage paths through dams	Entrapment and drowning
	Open spillways not visible from upstream (**Figure 10.3**)	Unintentional passage over weir and drowning
	Sudden changes in flow depth or conditions downstream of movable weirs	Drowning
	Breach of weir leading to flooding	People swept over by deep or fast flows, drowning, illness
Physical (**Section 10.3.3**)	Submerged hazards (difficult to spot, especially if turbidity affects visibility)	Foot entrapment and drowning, or puncture injury
	Vertical wing walls (**Figure 10. 3**)	Self-rescue not possible
	Steep or slippery surfaces and river-banks	Boaters unable to portage weir, assisted rescue difficult or impossible, slips, trips and falls
	Immersion in deep, cold water	Cold water shock, heart attack, hypothermia
	Movable gates, mechanical and electrical equipment	Entrapment, sudden increase in flow
Chemical (**Section 10.3.4**)	Contaminated sediment	Illness, death
Biological (**Section 10.3.5**)	Leptospirosis (Weil's disease)	Illness, death



Case A Swept-out jump

Tailwater depth < sequent depth

Hydraulic jump forms well downstream of the weir.

Case B Optimum jump

Tailwater depth = sequent depth

Hydraulic jump forms immediately downstream of the weir.

Case C Submerged jump

Tailwater depth > sequent depth

The most dangerous condition. A partially submerged hydraulic jump is formed against the face of the weir. It is relatively quiet and innocuous looking, belying a lethal capacity to trap victims.

Case D Drowned weir

Tailwater depth >> sequent depth

Hydraulic jump is drowned, leading to undulating surface waves and some recirculation below the surface.

Figure 10.1 Weir flow types (from Tschantz and Wright, 2011)

The hydraulic hazard at a weir can vary with flow and tailwater conditions and a weir that is innocuous during low flows may become hazardous during high flow conditions (**Figure 10.2**). When tailwater level is low, the weir may develop a strong towback, and deep, fast flow conditions when the hydraulic jump is drowned by a high tailwater level. This change in hazard can be imperceptible, particularly upstream of movable gates where the water level remains constant, but the flow varies.

Weirs with a steep or vertical downstream face and a uniform hydraulic jump with no weak points are particularly hazardous due to the difficulty of escaping, as are curved weirs (**Figure 10.3**). See also **Appendix A1.1.6**.

Another type of hydraulic hazard is breach leading to the sudden release of a large quantity of water and flooding downstream. Breach (or dam-break) analysis can determine the risk to people, which is related to the speed of inundation, depth and velocity of floodwater, debris load and the nature of the area at risk (Defra, 2008). Sudden operation of movable weirs can lead to similar, if less dramatic, conditions.

Note

The hydraulic hazard at this vertical drop weir is low during low-flow conditions, but during high flows it develops a strong re-circulating flow along the entire length.

Figure 10.2 Change in hydraulic hazard between low and high flow conditions

The only signs of this hazardous weir from the watercourse upstream are the vertical wingwalls and the horizon line, indicating a sudden drop in water level.

Self-rescue is difficult at this weir due to the uniform hydraulic jump and vertical wing walls. A bank-based rescue would be difficult due to the high walls.

Pulteney Weir, Bath is visually pleasing, but in high-flow conditions the vertical steps create a hazardous re-circulating flow, which has claimed several lives. Rescue is difficult due to the curved plan form.

Figure 10.3 Hazards at weirs

10.2.3 Physical hazards

Underwater hazards can cause injuries to people and animals, foot entrapment or puncture/damage boats. These can lead to drowning when water pressure pushes the victim's body downstream and they are unable to hold their head above water. Hazards include gabion baskets, uneven materials, structures in poor condition or undermined by scour, boulders, and cracks in bedrock. These are not always visible to the observer, although uneven flow over the crest or apron may indicate damage such as missing blocks or local scour.

Weirs with vertical wing walls at either side are particularly hazardous due to the difficulty of either self or assisted rescue. Steep or slippery river-banks or surfaces next to the weir can cause visitors to slip and fall into the river, or make access or egress difficult for water users and rescuers. This may also mean that boaters have no choice but to attempt to shoot the weir.

UK waters are classed as cold (10°C to 15°C) and a deep, cold weir pool downstream of a weir can present additional hazards. Cold water shock is the short-term involuntary response to sudden immersion in cold water, leading to hyperventilation and potentially heart attack, even in young and healthy people. Although this response subsides in time, there is a residual risk of hypothermia.

The operation of movable gates (particularly hand winding) can pose a risk to weir operators. The operation of gates can cause flows or water levels to change without warning, presenting a risk to anyone who is on or in the water nearby. Historic paddle and rymer weirs involve lifting boards against water pressure and present a manual handling risk.

10.2.4 Chemical hazards

Contaminants in accumulated sediments upstream of weirs can cause burns, illness or death. The risk of mobilisation during works in or around weirs increases the potential for short-term sediment disturbance, or direct exposure of contaminants to site operatives or members of the public. In addition, removal or alteration of a weir structure can alter the longer term movement and deposition of contaminated sediment downstream of the original source.

Where contaminated materials (chemical or biological) are known or suspected to be present, risk and Control of Substances Hazardous to Health (COSHH) assessments should be carried out before works start. Controls may need to be put in place before works can begin, and assessments should be reviewed and amended as they progress. Typical aspects to consider include protection of site staff and construction operatives, restricting access by members of the public and livestock, and potential impacts upon the surrounding environment (eg surface water, groundwater, nearby properties and rights-of-way).

10.2.5 Biological hazards

Biological hazards include waterborne diseases such as Leptospirosis (Weil's disease), which is caused by a bacterium transmitted through rats or cattle urine. Although not unique to weirs, warm bodies of retained water can provide an ideal environment for harbouring and transmitting the disease in the summer months. Humans may be infected when open cuts or mucus membranes come into contact with urine or contaminated water.

10.2.6 Weir assessment system

In the UK, a weir assessment system for hydraulic hazards helps determine whether urgent action is required to reduce risk. A summary is given in **Table 10.2** and full details are in Environment Agency and Rescue 3 (UK) (2009). The nature of the river downstream (**Table 10.2**) is described in accordance with the international river grading system (**Table10.3**).

Table 10.2 Summary of weir assessment system (after Environment Agency and Rescue 3 (UK), 2009)

Nr	Description	Low risk	High risk
Step 1: Assess hydraulic hazard for range of flow and tailwater conditions			
1	Towback distance	None	>5 m
2	Depth of hydraulic jump	None	>1 m
3	Height of drop over weir	None	>2.5 m
4	Slope of weir face (from vertical)	None	<30°
5	Floating debris in hydraulic jump	None	>25% of length of jump
6	Uniformity of hydraulic jump	Broken feature	Uniform
7	Sides of the hydraulic jump	Both open	Both closed
8	Orientation of hydraulic jump to approach flow	<30°	90°
9	Additional hazards in or downstream of the weir	None	In main flow
10	River bed composition at base	Drowned or non-modular	Rock, debris
Step 2: Assess the likelihood of harm based on access to the weir from land or water, control measures to prevent access and ability to self-rescue			
11	Public access from land or water	None	Access
12	Control measures to prevent people entering the weir (see **Section 10.3.3**)	Adequate	Inadequate
13	Ability to self-rescue (see **Section 10.3.4**)	Possible	Not possible
Step 3: Assess weir risk rating based on hazard and likelihood and priority for mitigation measures			
Step 4: Assess weir rescue difficulty and determine the need for action			
14	Distance across the weir	<10 m	>75 m
15	Access to both banks	Easy	None
16	Shape of the weir	Straight	Curved
17	Towback length	None	>5 m
18	Remoteness	Urban	Remote
19	Nature of river downstream (see **Table 10.3**)	Up to Class I	>Class III or downstream weirs
20	Working area on banks	Good	None
21	Anchors for rope system	Good	Limited
22	Available rescue technique (see **Section 10.3.4**)	Full range	Helicopter only
23	Height of bank above base of hydraulic jump/stopper	<1 m	>3 m

Table 10.3 *International river grading system*

Class	Description	Example
I	Fast moving water with riffles, small waves and few obstructions. Risk to swimmers is slight, self-rescue is easy.	
II	Straightforward rapids with wide, clear channels. Swimmers seldom injured and group assistance seldom needed.	
III	Rapids with moderate, irregular waves. Swimmers rarely injured, self-rescue usually easy, group assistance may be required to avoid long swims.	
IV	Intense, powerful but predictable rapids. Moderate to high risk of injury to swimmers, self-rescue difficult, group assistance for rescue often essential, but requires practiced skills.	
V	Long, obstructed, or very violent rapids. Swims are dangerous and rescue often difficult even for experts.	
VI	Rarely attempted. Consequences of error are severe and rescue may be impossible.	

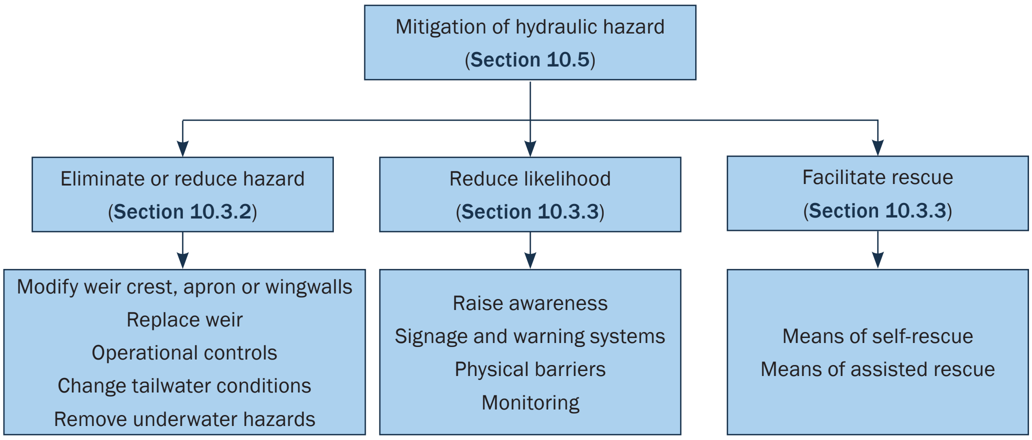


Figure 10.4 Mitigation measures

10.3 MITIGATION MEASURES

10.3.1 Overview

Mitigation measures fall into three broad categories as illustrated in **Figure 10.4**.

The choice of measures depends on factors such as conditions at the waterside, the presence of hidden hazards, and access to the weir from all directions (land on either bank or from the water up or downstream) and by whom (operations staff, member of the public and/or unaccompanied children). The likelihood of involuntary entry into the water due to crowd pressure should also be considered.

In the UK, water safety principles emphasise the importance of striking a balance between visitor self-reliance and management intervention (**Table 10.4**).

Table 10.4 Water safety principles (after National Water Safety Forum, 2014)

Principle	Detailed principles
Fundamental	No activity can be made completely risk-free. Risks imposed on non-participants and over which they have little or no awareness or control, can only be accepted if they are very low. Consider all benefits, dis-benefits and costs of water-related activities when judging whether risks are acceptable or further risk control measures are necessary. Learn from the past and look ahead by assessing the risks that can be foreseen. Avoid restrictions on access.
Responsibility	It is important to strike a balance between the self-reliance of the individual participant and management interventions. Everyone involved in a water-related activity has some responsibility for ensuring their own safety. Statutory bodies and responsible organisations may have only limited powers to require or enforce. Avoid risk controls that discourage people from organising or managing an activity, as far as possible. Children's risk perception skills will not be fully developed.
Partnership	People taking part in similar activities will accept different levels of risk. Risk control measures for one participant group may create risks to others. Work with visitor groups to promote understanding and resolve conflict. Collect incident data in partnership with others where possible.
Awareness	Ensure that people are aware of and understand potential hazards and risks. Inform and educate people about the nature and extent of hazards, risk controls in place and precautions they should take. Integrate safety information with other information provided to the public wherever possible.
Competence	Some people overestimate their skills and abilities to a certain degree, especially if impaired by alcohol or drugs. People have a range of abilities to recognise any given hazard. Some will overestimate, while others will underestimate and even fail to recognise a hazard exists. Where competence levels are deemed inadequate, training can improve competence.
Communication	Communicate the results of risk assessments and risk awareness material to participants, taking account of the language, literacy and cultural needs of the target audience.

10.3.2 Eliminate or reduce hazard

Measures to eliminate or reduce the hazard are passive and protect all user groups, including members of the public who do not always appreciate the risk associated with weirs and may be put at risk. These measures are desirable due to the emerging demand of the public to access rivers and weirs, and the associated issues, particularly in urban areas. Measures to reduce hazard are given in **Table 10.5 and Figure 10.5**. See also **Case study A3.10**.

Canoeists prefer to shoot a weir if it is safe to do so, as it is easier than portaging, and recommended safety features for weirs used by canoeists are given in **Box 10.1**.

Box 10.1 Safety features for weirs used by canoeists

Canoeists can shoot a weir at speed and may be able to overshoot (or 'boof') the towback, but this is risky and not advisable if the length of the towback exceeds half the length of the canoe (typically three to four metres).

Provide egress and access points above and below the weir, with a signed portage path parallel to the river, to allow canoeists and swimmers to exit the river above the weir, walk round the weir safely and re-join the river below.

Provide warning signs upstream of the portage so that canoeists can find the correct course to reach the portage safely.

Provide sufficient water depth over at least a portion of the crest to allow canoeists to negotiate the weir without grounding.

Provide an open-ended hydraulic jump that allows escape from either end, and a well-defined jet of water downstream of the weir to allow canoeists to escape the re-circulating hydraulic jump.

Provide sloping banks rather than vertical walls, which allow waves to break on them and dissipate energy.

Avoid bringing canoeists into contact with high or gradually accelerating flow velocities at abstraction or hydropower inlets or sluices, for example, by protecting the entrance of closed-ended inlet channels leading to sluices. Beware that a gently accelerating flow may pull canoeists or swimmers towards a hazard long before the hazard is visible. A velocity exceeding one metre per second is difficult to swim against and over 1.5 metres per second is impossible to paddle against.

Table 10.5 Measures to eliminate or reduce hazard

Measure	Description
Remove or replace weir	Remove weir and restore river. Replace with movable crest (eg hydraulically operated gates, inflatable dam or bascule gate with inflatable rubber bladder) (Schweiger, 2011).
Modify weir crest	Provide a chute for boaters to bypass a dangerous hydraulic jump. Remove a portion of the weir crest to create an irregular hydraulic jump (see **Case study A3.10**). Increase structure height to promote formation of a safer hydraulic jump (the required height can become too large to be acceptable) (Leutheusser and Birk, 1991).
Modify weir apron	Alter the weir apron (eg change the slope or add battens to deflect flow). Provide cascade with continuous energy dissipation (eg a rock ramp, grout bags or concrete steps).
Modify wing walls	Avoid or remove vertical wing walls and abutments so that swimmers can escape more easily or to facilitate assisted rescue from the bank.
Operational controls	Incremental operation of movable gates.
Change tailwater conditions	Alter tailwater depth to drown or change location of hydraulic jump.
Remove underwater hazards	Avoid or remove hazards that could cause puncture injury or foot entrapment.

This weir has an irregular hydraulic jump with a strong downstream chute (indicated by highly aerated water in the foreground) which will flush canoeists through.

Hydraulic deflector plates were installed downstream of a radial gate to disrupt the uniformity of the downstream hydraulic jump. These were orientated with omitted sections of the stilling basin end sill to provide flushing points in the downstream hydraulic.

This timber chute installed on part of an otherwise impassable weir allows canoeists to shoot a weir on a river in Germany. This is a common approach in mainland Europe

Figure 10.5 ***Measures to eliminate or reduce hazard***

10.3.3 Reduce likelihood of harm

Measures to reduce the likelihood of harm do not eliminate the hazard, but reduce the probability of someone entering the weir, either from land or water (**Table 10.6**).

A guide to selecting risk control measures for weirs with land- and water-based activity is given in **Tables 10.7 and 10.8**. Regardless of the approach taken, where asset owners have multiple weirs, risk control measures should be consistent between sites.

Table 10.6 ***Measures to reduce likelihood of harm***

Measure	Description
Raise awareness (**Box 10.2**)	Water safety education for water users. Provide information to professionals and stakeholders.
Signage and warning systems (**Box 10.3**)	Warning signs on river-bank directed towards water users rather than land users, showing recommended egress points well in advance of the weir. Manual warning boards or traffic lights. Audible alerts (eg sirens) at movable gates. Visual alerts (eg strobe lighting) at movable gates.
Physical barriers (**Tables 10.7 and 10.8**)	Safety boom upstream of weir to prevent access from the water (requires debris management and may create hazard to boaters) (**Figure 10.7**). Overhead warning boom upstream of safety boom. Safe egress point and portage around a weir for boaters. Safe moorings for boaters. Partial or full exclusion fencing to prevent access to the weir from land.
Monitoring	Video monitoring (CCTV or webcam). Police liaison and waterfront patrols.

Table 10.7 ***Risk control measures for weirs – land-based activity (after Canal & River Trust, 2012c)***

Conditions	Controls
Daily operational presence, no public access	A
Operational access required, open to public, minimal public use, no hidden hazards	A, B
Operational access required, open to public, minimal public use, hidden hazards present	A, B, C, D, E
No operational access required, open to public, occasional unaccompanied children, no crowd pressure	A, B, C, D, E
No operational access required, many visitors including unaccompanied children, possible crowd pressure	A, F

Key

A – no action
B – clearly defined edges or demarcation
C – means of assisted rescue
D – means of self-recovery
E – partial exclusion fencing
F – exclusion fencing

Table 10.8 Risk control measures for weirs – water-based activity (after Canal & River Trust, 2012c)

Conditions	Controls
Access to weir from navigation	A
Craft will ground before weir crest	A
Risk of craft trapping on crest or in turbulence below	B, C, D
Risk of craft overtopping crest	D

Key

A – no action
B – consider warning signage
C – cost-benefit analysis of options
D – install safety boom

Raise awareness

Awareness of the hazards due to weirs can be raised by providing information on the location of weirs, the hazard and the best portage route. In the UK, river guide websites provide this information (see **Websites**). There is also a need for public education, particularly where weirs are located near residential areas and used for informal recreation in the summer.

Websites

The UK Rivers Guidebook: **www.ukriversguidebook.co.uk**

British Canoeing Canoe Trail guides: **www.gocanoeing.org.uk**

Paddle Points: **www.paddlepoints.net**

The unintentional creation of new hazards should be avoided, and it is important to raise awareness with other weir owners and professionals. Hydraulic engineering textbooks tend to focus on the design of weirs for flow measurement, water level management or energy dissipation. There are very few that provide safety advice, so there is scope of greater coverage of safety issues.

Box 10.2 Reducing likelihood of harm by raising awareness

In Germany and Austria, 'Wassersport' 'Wanderkarten' or watersport maps provide navigation information on weirs, locks, white water grading and other features of interest, including large-scale diagrams of important weirs, clearly indicating the portages.

In Minnesota, USA, a public information leaflet describes the hazards due to weirs, what can happen and what to look for (Elverum and Smalley, 2003).

Signage and warning systems

Signage is the simplest approach and good practice guidance on signage is given in **Box 10.3**. If unauthorised or accidental swimming is a problem, 'No swimming' signs should be provided as a minimum, possibly with additional signs warning of hazards such as deep or shallow water, strong currents or underwater obstructions. More explicit signs such as 'danger of death' or a skull and crossbones warning will convey the message more clearly.

During implementation (whether removal, modification or construction), works at weirs should be signed for both land and water users to minimise the risk of boaters being put at risk by entering the works.

Where water levels are controlled by fixed crest weirs, an increase in flow results in both raised water level and velocity. On navigable rivers or waterways, the increased hazard can be indicated by water level against a gauge board and a passive warning system is sufficient.

Where movable weirs are used to control water levels, there may be an increase in flow velocity with little discernible change in water level. A boater may not be aware of the increased hazard and an active warning system controlled by operatives should be adopted. Manual warning boards, traffic lights, three phase warnings (green-amber-red) and gauge boards showing flow depth or air draught may be used. Trigger levels should be set to minimise the risk to the most vulnerable users such as hire boaters or new boaters. Warning signs should be located at a sufficient distance from the hazard to allow the boater to take evasive action, and must be visible to all craft. They should be accompanied by safe moorings where boaters can wait out a high flow event in safety. Further guidance can be obtained from the Canal & River Trust or from the Environment Agency on their navigable rivers.

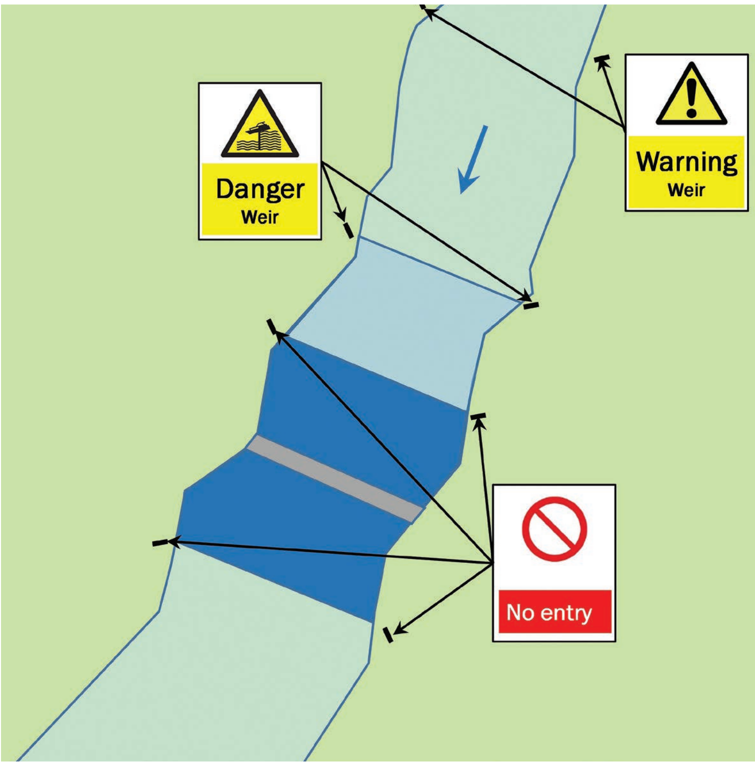
Hinged weirs (flap gates or sector gates) present little hazard when fully closed (vertical or near-vertical) or fully open (flat on the river bed). However, partially open, they create dangerous recirculating hydraulic jumps downstream that change as the gate moves and are impossible to navigate. It is important that water users are warned of their presence as they cannot be seen from upstream when looking downstream, and that emergency access to the weir on both sides and recreational access both over and around the weir on one side are provided.

Box 10.3 ***Warning, danger and restricted zones (from USACE, 2006)***

In the USA, public access is prohibited immediately upstream and downstream of all weirs owned by the US Army Corps of Engineers and any other structures with similar hazards (USACE, 1996 and 2006). Three zones are defined upstream and downstream of a weir:

- **Zone 1 Warning area:** boaters are warned of impending dangerous conditions.
- **Zone 2 Danger area:** boaters are notified that the weir is a specific distance ahead and that they are in immediate and grave danger.
- **Zone 3 Restricted area:** signs are placed to prohibit access.

The extent of a restricted area is based on hydraulic criteria and operational considerations. This is so that a boater upstream can reach shore before being carried by currents into the weir, or to allow a reasonable expectation of rescue in the event of an accident, and to prevent a swimmer or boat without power downstream of the weir from being drawn into it. The restricted area should also encompass areas of turbulent waters caused by the operation of the works that create significant risk of swamping or capsizing a small boat. Restricted area boundaries are based on high flow conditions, and do not vary with fluctuating flows, intermittent discharges, or seasonal variations.



Physical barriers

Physical barriers have advantages and disadvantages, for example fencing to prevent entry to the watercourse can prevent self-recovery from the river.

Safety booms should be provided if there is a risk of boats accessing or overtopping the weir crest. Those designed to restrain loose powered craft can be a dangerous barrier to unpowered craft, particularly in strong stream or spate conditions. Booms also collect debris, which can be dangerous to the public and costly to remove.

Install a boom at an oblique angle across a river (**Figure 10.6a**). This will direct the debris to one bank from where it can be removed more readily, and allows swimmers and boaters caught up in the boom to move along the boom to the bank. The boom end pile or fixing point should be on or set into the bank to allow self-rescue by people from the environment to the bank, and the bank should be easy to access and egress.

Avoid installing a boom at right angles across a river as it will sag downstream, taking up a 'U' shape in plan. This will accumulate debris in the centre of the river, and canoeists and swimmers trapped at the middle of the 'U' will be unable to get out, swim or paddle back against the current (the same issue as shown in **Figure 10.10**).

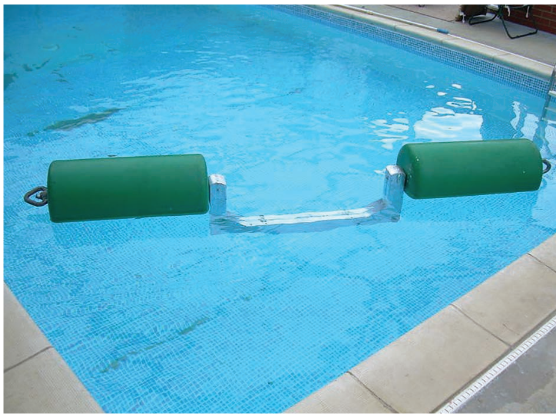
A boom stirrup can be installed within a boom to allow the passage of canoeists or swimmers while retaining the integrity of the boom. These comprise a prefabricated flat metal 'U' in profile whose length and fixings are identical to a single barrel and can be inserted anywhere along a boom by removing or replacing a barrel. The stirrup can be located to guide canoeists to the best route over the weir, to a dedicated canoe chute or conjunctive fish pass. Signage is unnecessary as canoeists who are sufficiently expert to shoot the weir will find the route (**Figure 10.6c**).

Safety booms may sometimes be needed at weirs on rivers with no navigation authority, to guide swimmers away from or guard hazards.

Options for canoe portages are shown in **Figure 10.7**. Some general design principles are given here, while more detailed guidance is available from British Canoeing (see **Websites**):

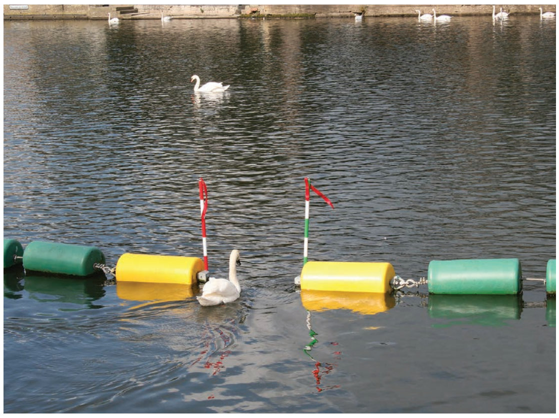
- Locate an egress in slack water, installing boulders upstream to create an eddy if necessary.

a A safety boom upstream of a weir should be installed at an oblique angle to direct debris towards one bank where it can be removed.



b A canoe stirrup inserted into a barrel chain can allow canoeists to negotiate through a boom to shoot a weir, seen here in a swimming pool.

c A canoe stirrup should wide enough for large canoes.



d Even wildlife can use the canoe stirrup.

Figure 10.6 Good practice for safety booms

- Steps should be solid, not undercut, to avoid trapping the gunwale of a canoe.
- Flat surfaces should be no more than 0.3 m above the water for ease of disembarking and all edges should be rounded.
- Small mooring rings are useful, but avoid handrails that trap debris and can get in the way.
- If using concrete, the surface should be tamped parallel with the flow direction to encourage self-cleansing and reduce the need for silt removal.
- Provide appropriate signage visible to both water and land users. This is particularly important on navigations where mooring boats can block a portage, leaving no gap for canoeists to egress.

Conjunctive fish passes provide sufficient width and draught for canoeists to pass in the downstream direction, while allowing fish to migrate upstream. Some options are shown in **Figure 10.8** and some general design principles are given as follows. More detailed guidance is available from British Canoeing (see **Websites**).

- The canoe chute should be 1.5 m wide with clear space for paddles on either side and a minimum draught of 0.3 m at Q95.
- The plunge pool should be at least one metre deep and three metres long, to allow fish to rest and prevent canoes from making contact with the river bed or Larinier baffles.
- The approach flow should be slow-moving water to allow canoes to tilt to the slope of the pass without grounding and to allow fish to rest.
- The entry and exit should be free from obstructions.
- Larinier baffles should be rounded to minimise damage to fish and canoes.
- Upstream wingwalls should be sloping to minimise debris accumulation.
- All exposed edges should be rounded to minimise injury to persons, equipment and fish, and to minimise debris accumulation.

Websites
British Canoeing: **www.britishcanoeing.org.uk**

Monitoring

Monitoring, police liaison and waterfront patrols may be worth considering if there is a risk of conflict between unauthorised visitors and other users.

Beaches are ideal if gently sloping with a clear length of five metres and a slope of 1:10 or less.

Slipways are the man-made version of a beach and can be cut into a suitable bank. A slipway should extend at least one metre below the lowest known water level without encroaching on navigation, and should have a slope of 1:10 (or 1:15 for the less able).

Steps are useful for steeper banks and should extend below water level. They should be 1.5 m wide (no less than one metre) on the approach and five metres wide at the water's edge to allow a canoeist to pull alongside.

Jetties are ideal if the egress is sited adjacent to deep water, in dense reeds or if the river-bank is very steep. Here, platforms at different levels allow access and egress as water level varies.

Floating pontoons are useful if the water level varies greatly or no other options are suitable, but require maintenance. They should have a flat surface no more than 0.3 m above water level and be capable of supporting at least two paddlers and their craft without excessive tilting.

Figure 10.7 Options for canoe portages (courtesy Chris Hawkesworth)

Side by side passes can be used where flow is sufficient. The inlet invert level of the canoe chute invert should be slightly higher than that of the fish pass invert to maintain flow to the fish pass during low flow conditions.

Here, a Larinier fish pass (on the right) and canoe chute were installed in a former by-wash. The bridge was raised to give extra headroom.

Conjunctive canoe/fish passes must provide suitable velocities for fish.

This brush-furnishedfish pass uses reed-like bristles which allow fish to thread through or over them whilst avoiding damage to canoes brushing over the top.

Rock ramps are more natural and can be designed to provide a clear passage for canoes down the rock ramp while allowing upstream fish migration. Strategically placed rocks at the sides cater for slower fish.

Figure 10.8 Options for conjunctive fish passes

10.3.4 Facilitate rescue

Measures to facilitate self-rescue or assisted rescue should be a last resort as they require active intervention, may be unsuccessful, and rescue equipment could be at risk of vandalism. Rescue methods suitable for weirs, their applications and limitations are given in **Table 10.9** and measures to facilitate rescue are given in **Table 10.10**. Further information on rescue methods is available in Ferrero (2006).

Table 10.9 Rescue methods suitable for weirs

Method	Description	Applications and limitations
Self-rescue	Swimmer swims across hydraulic jump to a weak point, pushes off the bed to escape the tow back or drops to bed and escapes with flow near bed.	Hydraulic jumps with a weak point. Any weir width. Residual risk of entrapment in objects on river bed.
Reaching rescue	Rescuer presents long object such as a paddle or pole to victim as a rescue aid.	Weirs with bridge above. Narrow weirs (eg < 4 m wide) with access to river-bank near victim.
Throw line rescue	Rescuer throws line or rope from bank or bridge.	Weirs with bridge above. Wider weirs (eg < 40 m wide) with access to river-bank near victim. Range ≈ 20 m, depending on length of throw line and rescuer's ability.
Live bait rescue	Rescuer attached to line jumps into watercourse and grabs victim – both are then pulled to bank by a belay team.	Requires team of suitably equipped rescuers. Rescuer must be willing to swim the rapid downstream if necessary.
Rescue with a large object	Rescuer presents floating object such as a canoe or lifebuoy on a line into weir for victim to grab.	Wide weirs, boat-based rescue from river downstream of weir.
Boat rescue	Rescue boat tethered at both banks approaches victim from downstream.	Wide weirs, boat-based rescue from river downstream of weir. Requires boat access to river and tethering points. Unsuited to weirs with white water rapids or another weir downstream.
Helicopter	Rescuer lowered on a winch attaches harness to victim who is lifted to safety.	Any weir. Unsuited to weirs with overhead power lines or overhanging trees.

Table 10.10 Measures to facilitate rescue

Type	Description
Self-rescue	Break in the hydraulic jump, a deep weir pool and egress points on both river-banks. Good access to weir from both land and water (eg low banks that are clear of vegetation, a bridge over or adjacent to the weir). Self-rescue equipment (eg grab rails, ladders). Horizontal chains along a vertical wall to allow someone to work their way along a wall, with egress at the end (eg steps) (**Figure 10.7**).
Assisted rescue	Good access to weir from both land and water for emergency services. Rescue equipment (eg life buoys, throw lines), although this carries a risk of theft or vandalism. Harness attachment points or rope belay points (eg mature trees, stakes in ground) (see **Figure 10.10**). Rescue training.

Figure 10.9 Measures to facilitate rescue

Belay points for boatwork should be installed obliquely across a river so that a rescuer can reach the safety of the bank easily (**Figure 10.10**). Installing belay points at right angles can allow the rope to sag in the centre of the river, forcing the rescuer to work against the current to reach safety.

Note

The horizontal chains installed on piers immediately upstream of a weir will facilitate self-rescue, should someone be unfortunate enough to miss the portage.

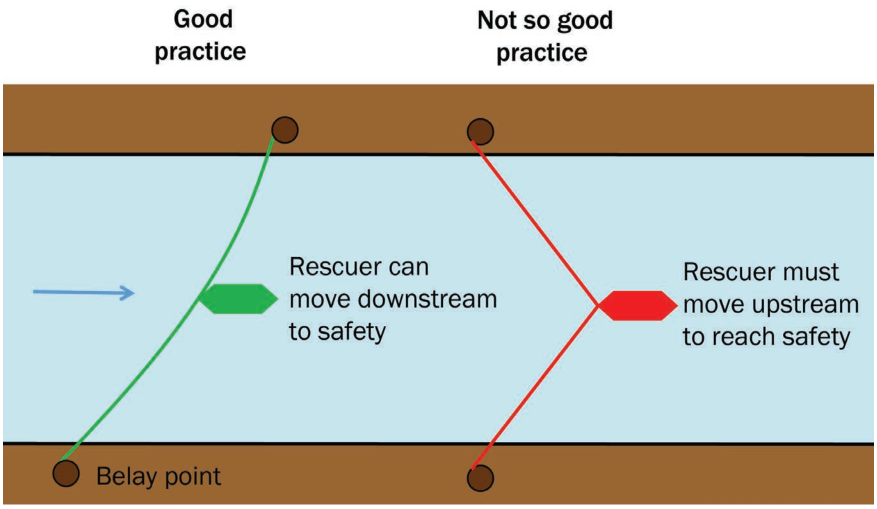


Figure 10.10 ***Belay points for boatwork***

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11 Natural and historic environment

11.1 INTRODUCTION

This chapter describes the environmental baseline that needs to be considered during any assessment of feasibility, planning and implementation of weir construction, removal and or modification. There are a number of legal duties relating to the environment and as well as a duty of care by public bodies for ecology and amenity. These are discussed in detail in **Chapter 9**.

This guide emphasises the importance of having an understanding of watercourse forms and processes (physical and ecological) so that suitable analysis can be undertaken to determine how the watercourse may respond to new weirs, weir removal or modification. The necessary assessments that would need to be undertaken, depending on the level of risk associated with the proposed works include:

- Geomorphological or hydromorphological assessment (see **Chapter 12**).
- Engineering feasibility assessment linked to the potential geomorphological or hydromorphological response of the watercourse to ensure surrounding infrastructure would not be compromised and what mitigation could be necessary (see **Sections 12.4 and 13.7**).
- Flood risk assessment to model the predicted effects of a new structure, modification or removal of an existing structure to ensure no detrimental impacts or flood risk are created, particularly downstream (see **Section 13.2**).

Issues covered in this chapter include:

- Water quality and contamination assessment for sediments currently stored behind the weir structure if there is a risk of sediment discharging downstream (**Section 11.4**).
- Ecological and fish passage analysis to determine how habitats and fish passage may change following construction, modification or removal (**Sections 11.5 and 11.6**). Such assessments might rely on the outputs of hydraulic modelling to determine more precisely the scale of impacts on hydraulic habitat.
- Heritage assessment to consider the heritage value of an asset as this may mean that works to install a new structure or remove an existing weir may not be possible and other options need to be sought (**Section 11.8**).
- Assessment of impacts on landscape and recreation (**Sections 11.7 and 11.9**). This may include consideration of the landscape and historic setting of a weir, the materials used and safe access to upstream and downstream stretches, and also the structure. Removal of a weir may affect amenity and aesthetics.

11.2 ENVIRONMENTAL CONSTRAINTS AND OPPORTUNITIES

The information gathering exercise should follow the approach outlined in **Chapter 3** to identify the site-specific constraints and importantly the opportunities. Collation of baseline background data should include statutory and non-statutory designations such as the presence of nationally and internationally protected sites and species as well as defining the user groups who may have an interest in the site. Often environmental issues are viewed as problems, but creative approaches can enable projects to achieve wider benefits than the original project aims. River projects have complex environmental interrelations between geomorphology, water quality, discharge and ecology, and the design, implementation of an in-channel structure needs to be developed with an awareness of these relationships.

When considering the design and construction of a weir, it should be possible to separate impacts into short-term construction impacts and long-term operation impacts, both of which may require differing mitigation measures, or simply good planning in advance.

11.3 TIMING AND SEQUENCE

The best time for carrying out engineering works in a river is normally in the summer (ie when flows are at their lowest), but this is often the time when adverse environmental impact is likely to be greatest and recreational use at its highest. A compromise is often required. With good planning and consultation it is possible to minimise the impacts without unduly compromising the engineering operation (or greatly increasing the cost). Particular seasonal activities to avoid will be specific to the site in question, but in general could include:

- angling, especially organised events and competitions
- navigation and boating (the 'stoppage period' for the Canal & River Trust is between 1 November and 31 March, shorter or non-existent for some waterways)
- presence of protected species (for details on avoidance and mitigation measures for different species see Newton *et al*, 2011)
- coarse fish migration, spawning and ova development ('closed season' will vary throughout the UK, but is typically mid-March to mid-June inclusive) and salmonid migration, spawning and ova development ('closed season' again will vary, but is typically October to March inclusive).

11.4 WATER QUALITY

11.4.1 Weirs and water quality

The water quality impact of weirs primarily relates to changes in dissolved oxygen. Typically the water retained by the weir experiences oxygen depletion (eg Butts and Evans, 1983), and water is subsequently reaerated while flowing over the weir.

Thermal impacts are also important. Water retained upstream of a weir is likely to be warmer than the natural stream state, and this can have further impact on the dissolved oxygen concentration. The resuspension of sediment during construction, modification and removal can result in increased turbidity and the mobilisation of other pollutants (such as heavy metals). However, these effects are typically temporary in nature and can be mitigated through good construction practice.

11.4.2 Impact of existing structures

Dissolved oxygen

Pooling behind weirs often results in low levels of dissolved oxygen because:

- Reaeration is reduced (reaeration is proportional to stream velocity and inversely proportional to depth).
- Biological and chemical oxygen use is increased (increased retention time allows microorganisms to use more of the available dissolved oxygen).
- Accumulation of sediments is known to occur behind weirs and these sediments, especially if polluted, can consume oxygen (sediment oxygen demand (SOD) is proportional to retention time and inversely proportional to depth).

Elevated dissolved oxygen levels upstream of weirs are also possible. Nutrient-rich water may promote excessive algal growth upstream of a weir resulting in photosynthetic oxygen production during the day, which can lead to supersaturation, ie a negative oxygen deficit.

Where upstream oxygen levels are supersaturated, flow over the weir can cause deaeration. Reaeration of flow over a weir (which is more typical) occurs where upstream oxygen levels are under-saturated.

Reaeration (or deaeration) over a weir is controlled by:

- differential water levels
- air and water temperatures – aeration over a weir increases linearly with water temperature
- weir design, including water depth at the foot, weir height, depth of water on a spillway, hydraulic jump presence at the weir base
- water quality – many contaminants suppress reaeration, including surfactants, sewage and sewage effluent (Kothandaraman, 1971).

Water quality and sediments

Weirs are well known to attract a build-up of sediments immediately upstream where the slow-moving water allows the settling of suspended particles. As well as an impact on the sediment regime, these sediments may harbour contaminants and nutrients, and have an oxygen demand (see **Section 12.5**).

The general impacts associated with in-channel structures, in addition to impacts upon sediment supply, includes the potential for pools behind weirs to exhibit higher than expected levels of nutrients. In combination with other effects upstream of weirs (stable flow conditions, warmer water), elevated nutrient concentrations can increase the risk of algal blooms in pools. This is likely to be more problematic where nutrients bind to suspended sediment, subsequently contained in a slow moving area of water behind a weir. The resulting acute impacts include hypoxic conditions leading to fish kills (Ram *et al*, 2014). Further detail on the potential biological and chemical changes that can be induced in a water column because of sediment deposition behind structures can be found in Baccus (1980), which used examples from the Grand River Basin in Ontario, Canada.

Water downstream of a weir may be 'cleaner' with fewer suspended solids. This is not necessarily a positive effect on the downstream watercourse as the environment may be reliant on the suspended solids (eg for nutrient transport) (Bednarek, 2001).

Temperature

Temperature changes both upstream and downstream of weirs can result from the water being retained by the structure. In pools behind larger weir structures, temperature stratification may occur if the upper surface is warmed (by warmer air and solar radiation) becoming less dense than the cooler water at the bottom of the pool. Without mixing, this temperature stratification is retained and the design of the weir structure is important in controlling the downstream water temperature, depending on where in the water column the downstream water is drawn from. Water behind smaller weir structures (ie retained in shallow pools) is likely to be warmer than for the natural stream state.

Changes in water temperatures can also influence other aspects of water quality. For example, dissolved oxygen saturation is controlled by water temperature – the solubility of oxygen decreases as temperature increases (ie warmer water can hold less oxygen). Reaeration of water flowing over a weir is also directly proportional to the water temperature so that warmer water reaerates more quickly than cooler water.

For salmonid species, stress and infectious diseases usually increase when water temperatures are at their highest and correspondingly when flows are at their lowest (De Leaniz, 2008). Further ecological impacts are discussed in **Section 11.6**.

Warmer water may increase the risk of Leptospirosis, which can be spread to people by contact with water contaminated with rats' urine. The warmer water upstream of a weir may be an attractive environment for rats. If Leptospirosis is suspected then people should be advised to avoid contact with the water.

11.4.3 Weir design and reaeration

The efficacy of weirs to provide a increase in dissolved oxygen in the water environment is generally of limited benefit when consideration is given to the effect weirs have on the whole channel profile. While water is indeed aerated when falling over a weir, the general impact of such structures is to reduce the gradient of the channel upstream, which lessens the possibility for natural re-oxygenation.

A weir's primary purpose should not be to aerate the water, nor should this be a justification for retaining a weir. However, weir design can strongly influence the amount of reaeration (or deaeration) that occurs in the flow over the structure and it is important to design the structure sympathetically. Some points to consider are:

- Use of reaeration of flow over the weir to off-set the oxygen depletion occurring immediately upstream of the weir.
- Management of supersaturation (eg due to algal blooms), perhaps by operating an undershot sluice adjacent to the weir during periods of supersaturation (described as follows).
- Whether foaming is likely to occur due to the presence of (sometimes naturally occurring) surfactants.

Flexibility of design could be important for managing ecological water quality. For example, algal blooms can result in supersaturation during the day (up to 180 per cent saturation), but much of this is taken up during respiration of algae overnight. If the supersaturated water passes over a weir, the excess dissolved oxygen could be lost, which may result in very low dissolved oxygen values when respiration occurs. In this situation, a weir and an undershot sluice could be operated such that the sluice is used when the water is supersaturated (minimising the loss of dissolved

oxygen), then the weir is used when there is oxygen deficit (to reaerate the water) (DoE, 1973).

In some situations it may be desirable to design a weir to minimise aeration. Where foaming is known or likely to occur, minimising aeration may reduce the appearance of foam (which can concern the public). For foaming to occur, the water must contain a surface active agent, or surfactant – foam formation also requires a source of gas bubbles, such as during aeration of flow over weirs. The presence of organic and inorganic particles can cause very stable foams to occur. Surfactants can occur naturally in the environment (eg decomposition products), but could also be from pollutants (Schilling and Zessner, 2011).

11.4.4 Impact of construction and/or modification

During construction (new-build or modification) of weirs, the water quality impacts primarily relate to turbidity (due to sediment resuspension) and the associated contaminants absorbed to the disturbed sediments.

Good construction management, such as temporary bunds to divert flows around the construction area, should be employed to control sediment resuspension and sediment mobilisation. Temporary diversion channels should be carefully selected and reinstated to ensure that they are not re-opened during flood flow conditions.

Where existing weirs are undergoing modification, consideration should be given to the influence of the weir design on the amount of reaeration (**Section 11.4.3**).

11.4.5 Structure removal

The impact of structure removal typically results in effects of a temporary nature, usually increased turbidity. Experience from UK river restoration projects indicates that turbidity impacts are often localised in nature (RRC, 2013). In channels with lower gradients, downstream deposition of sediment may prove problematic if there is no significant flushing effect. In these cases, more specific measures may be required to control sediment at source or modify the channel in the receiving reach to encourage mobilisation of sediment.

In old industrial areas, particularly within urban areas and areas of historic mining, industrial (and possibly domestic) legacy may result in a build-up of contaminants behind structures, reflecting the discharge consenting standards of the past. In these cases, detailed investigation of the sediment behind a weir structure is important, as impacts may be more significant compared to sediments that are relatively pristine (see **Section 12.5**).

Feld *et al* (2010a) reviewed the literature on weir and dam removal and found that decreased water temperature and increased dissolved oxygen upstream was a consistent effect of weir removal. Changes in temperature and dissolved oxygen are likely to be immediate, however changes in ecology may take many years and are related to the timescales for sediment recovery. The short-term impacts on water quality of weir removal include:

- **Sediment mobilisation leading to increased turbidity** – recovery time is usually short and depends on the length of time that the sediment has been accumulating, the velocity and gradient of the river, and the management of sediment during weir removal (see **Section 12.4.2**).
- **Release of contaminated material** – fine sediments tend to sorb more contaminants than coarse sediments (due to a larger ratio of surface area to volume). Contaminants could be toxic substances that were historically released upstream.

Some UK case studies in which sediment mobilisation has been minimised during weir removal can be found in RRC (2013). This includes an example of using bunds to direct flow around a weir during removal – the majority of sediment was removed along with the weir without disturbance by the flow and subsequent transport downstream.

Further guidance on techniques to manage sediment resuspension during weir removal is provided by the American Society of Civil Engineers (ASCE, 1997).

It is worth reiterating that these effects of weir removal are temporary in nature and recovery times from weir removal are very short (Bednarek, 2001).

11.4.6 Monitoring

In the UK, the environmental regulators (Environment Agency, NRW, SEPA and NIEA) are responsible for monitoring waterbodies for compliance with the WFD. This monitoring is unlikely to provide sufficient level of detail for an individual weir construction, modification or removal project.

The WFD requires 'no deterioration' of a waterbody, so the water quality impacts of any weir construction project must be considered, and the environmental regulator must be consulted.

For weir removal projects, it is important to undertake sediment sampling behind the weir to identify contaminants and composition of sediment (particularly potentially harmful finer sediment particles). Appropriate construction management techniques can then be applied to manage the risks associated with the disturbance of these sediments.

If a weir is to be modified, monitoring to establish the present condition of the waterbody immediately upstream and downstream of the existing weir will allow a robust scientific assessment of the effects of any proposed changes.

Monitoring of pre and post-construction water quality (upstream and downstream of a weir) is useful to establish the impact of the changes to the structure, and may help to justify the expense associated with any such project. However, such monitoring is undertaken infrequently and so the scientific evidence for the benefits of weir removal tends to be qualitative rather than quantitative.

Hammond *et al* (2011) includes monitoring strategies and is intended to support evidence gathering to demonstrate the effectiveness of river restoration projects.

11.5 FISHERIES

11.5.1 Overview

As environmental receptors sensitive to weir removal, modification or construction, fish need careful consideration during scheme design, from both construction and operational phase perspectives. A variety of environmental legislation exists that requires potential disturbance to fish to be considered. This may require fish passage to be included in design solutions or seasonal constraints for construction due to, for example, spawning. Legal requirements are discussed in detail in **Chapter 9**. Wider aquatic and terrestrial ecology is discussed in **Section 11.6**.

11.5.2 Operational phase and objective considerations

The need for consideration of operational phase impacts is in part dictated by fish biology and the significant mobility and species-specific seasonal, sometimes daily, longitudinal migration patterns of a large proportion of fish species found in the UK. Where weir design may lead to structures that delay or prevent such migration, a variety of environmental legislation exists that requires the inclusion of design features that attempt to mitigate for such impacts and assist fish passage across in-channel structures.

Legal responsibility for consideration of fish in the operational phase of weir works is covered in **Chapter 9**. It is worth noting that for all EU member states, the WFD represents a significant driver for measures to address factors limiting populations at a waterbody-scale. Fish are a specific ecological quality indicator listed in Annex V of the WFD. Where designs are likely to disrupt fish migration and have population as well as waterbody-scale impacts (eg by restricting access to habitats and limiting recruitment), designers should be aware that regulators may require inclusion of features to facilitate fish passage in weir designs. However, it should be noted that careful design to facilitate fish passage does not overcome impacts associated with the creation of impoundments and consequent effects on habitat type and availability.

Council Directive (EC) No 1100/2007 (The Eel Regulations) specifically prompts member states to consider measures to render structures passable as part of their eel management plans. Enactment of such European legislation at a national level also more specifically and robustly empowers some UK regulators to require developers to include fish passage features as part of scheme designs. For example, Section 14 of The Eels (England and Wales) Regulations 2009 empowers the Environment Agency to require the inclusion of eel passage measures when structures that could obstruct migration are being altered or constructed.

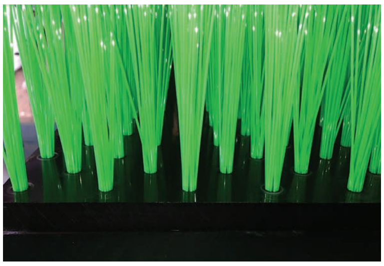
Armstrong *et al* (2010), FAO and DVWK (2002), Schmutz and Mielach (2014) and Larinier *et al* (2002) all describe approaches for fish pass measure design as well as critical design considerations for developing robust solutions.

This section signposts the previous information and other guidance rather than repeating detailed content. It is evident that the list of potential considerations when approaching fish pass design is substantial. The subject is further complicated by the variety of potential solutions that can be applied. A thorough understanding of the environmental baseline (including fish population, hydrology, geomorphology and spatial constraints) will help screen out unsuitable options and prompt designers towards appropriate solutions.

The principal design guidance previously cited gives useful steerage on the types of passage facility commonly applied and information on their hydraulic design. Armstrong *et al* (2010) present a fish pass selection matrix that gives a useful summary of which measures are best applied in which situation. **Table 11.2** describes the different fish pass types and design concepts.

Table 11.1 Summary of commonly applied fish pass designs

Type	Sub-type	Example
Close-to-nature Solutions involving constructed bed slopes designed to disperse the difference in level between a weir and the downstream water surface, usually mimicking a natural channel in terms of bathymetric, sediment and water velocity heterogeneity, but also sometimes plan form.	**Bypass channel** Usually a channel at a low gradient excavated outside of the existing channel. Depending on head difference across the structure, the channel can consist of a contionuous slope incorporating larger boulders to create regular flow refuges, or a series of pools (see *Technical – Pool and traverse*) formed by the placement of large boulders. See also **Case study A3.14**.	
	Ramp As bypass channel but often created in the existing channel.	
Technical Constructed solutions often designed to deliver more consistent and precise hydraulic performance than close to nature passes through the application of homogenous geometric arrangements.	**Pool and traverse** Fish swim through notches or traverses in vertical walls which create pools designed to dissipate energy caused by the cascade at each drop in head.	
	Baffle Used in a variety of repeating geometries, designed to reduce water velocity. Baffle arrangements are often deployed in culverts to assist passage.	
	Slot Similar to pool passes, but traverses extend the full height of the walls between pools.	

Type	Sub-type	Example
Other	**Fish lift/lock** Fish swim into a cradle which is then actively lifted from the downstream to the upstream side of the barrier. Similar to lifts, locks actively allow the passage of fish, but between a series of pools at progressively higher fixed elevations.	
	Bristle Bristle or boss tile substrate can be arranged in a variety of ways to provide surfaces that enable anguilliform-bodied fish to migrate past a structure.	

11.5.3 Construction phase

All proposed mitigation should be designed in consideration of the general principles of environmental and ecological impact assessment (see **Section 6.3** and IEMA, 2006). All proposed mitigation should be designed in consideration of the general principles of ecological impact assessment (see CIEEM, 2016). In development of an understanding of the baseline fish population of the catchment or reach in question, designers should consider the sensitivity of the fish species present to disturbance and the likely life stages present, in order to plan works so that they occur outside of critical periods such as spawning or hatching. Early engagement with local regulatory authorities will ensure that design criteria are clarified at an early stage. Angling closed seasons (which vary around the UK) provide a good indication of key sensitive periods relating to spawning.

In addition to published guidance on EIA, it should be considered good practice to undertake most in-channel works in the dry, as a means of reducing the risk of acute and chronic effects of pollution events on fish as a result of both sediment mobilisation and accidental chemical spillage. Designers should also consider the need to remove fish from any proposed area to be dewatered. Fish removal (or 'rescue') should be carefully planned to ensure efficient delivery and minimise the impact of stress on any fish in the dewatered area. Removal is best done by a combination of slow drain down (to aggregate fish into manageable areas/pools), and the use of netting or electric fishing gear. Using such instruments is often regulated, so should only be undertaken by individuals with experience of using such equipment and with an understanding, and in possession of, all required consents. Fish pass approval is discussed in **Section 9.7.3**.

11.5.4 Monitoring

Monitoring the movement of fish past a particular location can provide valuable information on the effectiveness of an installed fish passage facility, both in terms of whether fish can actually use a structure and the degree to which it delays migration. Monitoring the effect on fish populations of either weir installation or removal projects can be done by a variety of means. The direct survey of population size/strength is most reliably undertaken using quantitative electric fishing techniques (depletion sampling within a defined survey area), although cost often forces a compromise where multiple survey sites are concerned. In this case, relating semi-quantitative catch to sampling efficiency derived from quantitative survey methods can be a cost-effective alternative (Cowx, 1983).

A variety of passive monitoring technologies are available for this purpose:

- **Resistivity counters:** these use the difference in specific electrical resistance between fish and water to detect fish passing electrodes embedded in a structure. However, they are limited in that they cannot speciate fish.
- **Acoustic counters:** can be either active or passive systems that are usually reliant on a transducer emitting an acoustic 'ping' which is then detected by a receiver (static or hand-held). These are limited in that acoustic tags have to be surgically implanted into individual fish (commonly a regulated activity) and so are costly.

- **Optical counters:** can use photographic (stills or video) or infrared technologies (the breaking of an array of often infrared beams produces a silhouette of the fish, from which size and species information can be derived, depending on the quality of the image).

Detail on fish counter technologies and how they can be integrated into fish passage measures is available in Fewings (1994).

11.6 AQUATIC AND TERRESTRIAL ECOLOGY

11.6.1 Overview

Aquatic communities are a function of morphological, physical and chemical factors that are present at any time and location within a waterbody. Aquatic ecosystems continuously vary from its headwaters to the sea in what is described as the River Continuum Concept (RCC). The presence of a physical barrier such as a weir can interrupt this continuum due to loss of habitat connectivity and may result in impacts both upstream and downstream of the artificial barrier.

A description of potential changes in aquatic communities and ecosystems are described as follows, relating to the different stages of the lifetime of a structure. Specific issues related to fish and fisheries are described in **Section 11.5**.

It should be noted that the WFD requires that the current and future status of a waterbody be considered when all new activities in the water environment are planned. The requirements of the WFD need to be considered at all stages of the river and coastal planning and development process. The WFD further requires that environmental objectives be set for all surface and groundwaters in each EU member state. The Environment Agency is the statutory authority on the WFD in England and Wales and has produced guidance on assessing impacts of new schemes (Environment Agency, 2010a).

11.6.2 Ecological evaluation

In order to work towards achieving good ecological status (or no deterioration of current status) in compliance with WFD requirements, a good understanding of the physical and ecological status of watercourses as well as their processes is key to evaluate both the watercourse status, and ecosystem responses to new weirs, as well as weir modification and removal. This will enable the assessment of potential impacts of the proposed works and predict the future ecological status.

The ecological evaluation needs to be closely related with other geomorphological and hydromorphological assessments. This will help to determine how habitats might change following structure modification or removal. These assessments will need to be linked with any hydraulic modelling undertaken.

Baseline ecology information may be available for the watercourse and associated terrestrial habitats, but it is more likely that additional baseline surveys will be required. A desk-based review of the availability and suitability of the existing information and records would establish the requirement for further baseline surveys. The in-channel surveys may include:

- **River habitat survey (RHS):** a standardised methodology to characterise and assess the physical structure of freshwater rivers and streams. Each survey is carried out over a 500 m stretch and records the physical attributes of the banks and channel (such as material present, modification, flow types) as well as information about the riparian habitat. RHSs need to be carried out by certified surveyors and follow the latest methodology (Environment Agency, 2013c).
- **Species surveys:** including Macrophyte surveys following WFD-UKTAG (2014) guidance, macroinvertebrate surveys (following ISO 10870:2012) and fish surveys (discussed in **Section 11.5**). If the presence of invasive species is identified during the habitat surveys or desk-based studies, detailed invasive species surveys may be required (eg signal crayfish *Pacifastacus leniusculus* and/or invasive aquatic and terrestrial plant species).

These surveys may be combined with mesohabitat mapping to determine the presence and location of habitats for protected species. The need for specific protected species surveys can be identified at this stage. These surveys will also constitute a baseline to compare future data against.

Terrestrial habitats will also be affected by the works through site compounds, storage of materials and potential changes to the river regime and bank profile.

A condition assessment of nearby habitats (wetland and terrestrial) that may be affected by a proposed scheme should be considered. A phase 1 habitat survey will provide a first evaluation of the habitats present and the conservation importance as well as the presence of suitable habitat for protected species (JNCC, 2010). Following this, further surveys may be required to assess the presence of habitats and species of conservation importance. These surveys may need to be undertaken by licenced surveyors and be limited by seasonal constraints (for details on avoidance and mitigation measures for different species see Newton *et al* (2011)).

11.6.3 Impact of existing structures

In-channel structures result in impoundment of a section of the river reducing the gradient of the channel upstream with a corresponding reduction in velocity and increase in water depth behind the weir. Downstream of the weir, significant changes to the hydrological regime and sediment transportation may occur, altering aquatic habitats. The presence of the weir may also push aquatic species to habitat conditions near or beyond the expected range.

Existing structures can affect aquatic ecology through the following:

- changes in water quality
- changes in the flow regime
- changes in substrate
- loss of connectivity between upstream and downstream habitats
- creation of an impoundment upstream of the weir creating differing conditions in velocity and depth upstream and downstream
- increase in limnophilic species (species adapted to still waters such as carp)
- barrier to fish migration.

As noted in **Section 11.4.5**, temperature changes both upstream and downstream of weirs can result from the water being retained by the structure. In deep pools behind larger weir structures, temperature stratification may occur, which may create anoxic conditions due to decomposition processes and respiration rates. Without mixing this may impact on aquatic communities including macroinvertebrates, macrophytes and fish. Increased water temperature may lead to a development of phytoplankton and phylamentous algae, an effect which can be exacerbated during reduced flows. The design of larger weirs may allow the release of water from deeper layers to mitigate this problem. Monitoring of the dissolved oxygen levels needs to be undertaken to ensure that the released water does not create unfavourable conditions downstream due to low oxygen content.

In cases when the weir exists for water abstraction and/or energy production the operation of the weir and water intake may also mean that the flow pattern throughout the year will be significantly altered. This can lead to:

- Impacts due to alteration of flow patterns (eg riparian zone degradation, increased habitat for invasive species or loss/disruption of ecological function).
- Increased dry-spell duration (leading to decline of water level and wetted perimeter and loss of suitable habitat, reduction of riffle habitat and pools, and habitat diversity, loss of connectivity between viable habitat patches).
- Reduction of small floods/high flow pulses causing:
    - lower frequency of substrate-disturbing flow events and reduced benthic invertebrate species richness as fine sediments accumulate
    - changes in channel geomorphology
    - limited floodplain inundation which results in reduced invertebrate and fish biomass due to loss of flooded habitat and food resources supporting growth and recruitment
    - decrease in inter-annual variation in flood frequency which results in a decline in overall fish species richness as habitat diversity is reduced
    - potential encroachment of terrestrial vegetation and invasive species to the bed of the river
    - reduced diversity and biomass of fish and macro-invertebrates.

The WFD requires the development of procedures to ensure the adequate mitigation of negative impacts created by water abstraction and impoundments. This includes the need to address mitigation for alterations in the flow regime that ultimately will have an effect on the aquatic communities and ecological status or potential. Guidance on environmental flow releases from impoundments, to implement the WFD, provides

a method to evaluate the effects of the altered flow regime and a process to determine an environmental flow regime (Acreman, 2007). It describes the process of defining the target river ecosystem status, setting flow regime releases from impoundments and monitoring their effectiveness in achieving that status. It also provides a method for initial assessment of whether a waterbody is likely to fail to meet 'Good' ecological status because of changes to the flow regime (indexed by simple flow regime statistics). In addition, a method to define an environmental flow regime release based on the requirements of riverine species for basic elements (building blocks) of the natural flow regime, is also given.

11.6.4 Impacts of weir construction or modification

Construction effects are largely temporary and mostly result in changes in water quality and flow regime. It should be noted that the impacts from weir construction may not be limited to aquatics, but may extend to nearby land due to associated structures and access to the construction site. An assessment of the presence of protected species and habitats within the zone of influence of the scheme must be undertaken.

The effects of structure modification will depend on changes to hydrology after the changes are completed. The horizontal connectivity might be affected with a reduction in water depth, groundwater, water table and floodplain inundation. This could have negative effects on adjacent wetland-dependent communities and marginal riparian communities, reflected in a loss of nutrients in the floodplain. The modification of an existing structure may constitute an opportunity to integrate measures that will help in complying with the implementation of the WFD objectives. As part of the ecology status evaluation of a waterbody, specific measures are set to ensure that waterbodies achieve the stated environmental objectives. These are listed within the programme of measures for each RBMP. These measures are intended to mitigate impacts caused by human activity, with the aim of enhancing and restoring the quality of the existing environment. So an evaluation of the proposed mitigation measures for the relevant waterbody is recommended. Guidance on mitigation measures to deliver the WFD objectives are set out in Environment Agency (2013b).

11.6.5 Impacts of weir removal

Weir removal measures have been increasingly implemented in the past couple of decades. This is a response to increased concerns in regards to threatened and endangered fish species, physical fragmentation of river systems and the need to restore ecological and geomorphic function of rivers (Poff *et al*, 1997).

The primary aim of weir removal is to restore the longitudinal connectivity of streams and rivers. Weir removal can help the flow of migratory fish and benthic macroinvertebrates. In addition, there are positive effects on flow conditions and sediment particle size upstream, and water temperature up and downstream (**Section 11.4.5**).

Feld *et al* (2010a) conducted an important literature review on the ecological effects of weir removal. A general increase in macroinvertebrate, macrophytes and fish community diversity, and in certain cases biomass, was observed in many studies after weir removal, although most studies are based on qualitative data. The re-establishment of pre-impoundment river conditions, such as sediment transport, riffle/pool sequences, gravel and cobbles, appeared along with increases in biotic diversity (Bednarek, 2001). It was also clear that in some circumstances, many decades can pass before improvements become visible and in the short-term, negative effects are likely to dominate (eg mobilisation of fine sediments).

Negative effects may include:

- requirements to dispose of sediment
- increased turbidity for an undetermined period of time
- disturbance in what could be a stable-adjusted system leading to change in habitats, flora and fauna and consequent disruption of ecosystem processes
- loss of wetland habitat.

Experience in the UK from river restoration projects indicates that turbidity impacts are often localised in nature. In streams with lower gradient and energy, the deposition of sediments downstream may alter the substrate characteristics if there is not a sufficient flushing effect. In these cases, specific measures may be required to control sediment at source or look to modify the channel in the receiving reaches to encourage mobilisation of sediment.

When considering the option of removing a weir the positive gains for river habitats and species needs to be balanced against the likely changes to existing habitats and species upstream.

The removal of a weir needs to be considered and evaluated on a case-by-case basis. The decision should take into consideration the environmental objectives set out in the RBMP as part of the WFD process. Generally, the removal of a weir should be seen as an opportunity to deliver these objectives.

Other relevant legislation includes the Habitats Directive and Directive 2009/147/EC (Wild Birds Directive) as well as national legislation. In the UK public bodies have the duty to conserve and enhance biodiversity (see **Section 9.4.1**). Consideration needs to be given to species of conservation importance that are supported by the artificially created habitats and waterbodies affected. For example, the effects on white-clawed crayfish (*Austropotamobius pallipes*) must be considered where there is an existing population. Temporary relocation may need to be considered while weir removal works are carried out. The stream conditions after removal must be such that provide the suitable habitat to receive the population once temporary effects (eg increased turbidity) are reduced.

The need to identify the presence of in-channel, riparian and/or bank invasive species is important to prevent their spread during and after works. If an invasive species is identified as present in the area of influence of the works a specialist may be needed to provide advice on good practice to prevent the spread and/or removal if required. The GB non-native species secretariat provides more information and tools on biosecurity, a database of invasive species and species alerts (see **Section 9.4.8** for legal framework and **Websites**).

The interrelationships between the watercourse and the adjacent habitats are also important. An existing weir may be in place to control water levels to support adjacent land uses and habitats. In some areas of the UK, past engineering works, dredging and canalising rivers has separated the river from the floodplain. So much so that the mean summer water level of typical small Midlands rivers is now estimated to lie 1.5 m below bank top rather than the expected half a metre or less for a stream in its natural state.

Websites

GB NNSS: **www.nonnativespecies.org/home/index.cfm**

Box 11.1 Past dredging works isolate the Longdon Brooke, Longdon Marsh Nature Reserve, Rugeley, Staffordshire

Longdon Marsh Nature Reserve, managed by the Worcestershire Wildlife Trust, is an example where past dredging works have isolated the Longdon Brook from the associated floodplain and weirs supporting higher water levels were removed in the 1970s. As such, managing the adjacent Longdon Marsh for breeding wading birds and as a flood storage area for the downstream River Severn, is difficult to achieve without consideration of weirs. However, introducing weirs would run contrary to the objectives of the WFD of creating a more naturalised river state, and nearby landowners perceive that they would be subject to more upstream flooding if in-channel structures were constructed. These conflicting interests for the management of the marsh are difficult to resolve.

11.6.6 Mitigation measures

A data gathering exercise will inform the assessment of mitigation measures, which can help to avoid or reduce potential impacts of weir construction, modification and/or removal. RRC (2013) includes information on specific restoration and mitigation measures suitable to mitigate and/or enhance river habitats. In addition Environment Agency (2013b) provides guidance on mitigation measures to deliver the WFD objectives.

As with the construction of many structures to the side of a watercourse, there are often opportunities to improve habitats. These may include:

- sand martin burrows in wing walls upstream and downstream of a weir
- nesting ledges for dippers to the side of a weir
- overhangs beneath which swallows, swifts and martins can construct their nests
- damp conditions to either side of a channel for the proliferation of bryophytes and lichens
- overhangs immediately above the water to provide refuge to fish from predators
- low in-stream obstructions set into the bed of the river such as heavy boulders, downstream of which deeper areas and slack water should form (note that such features may present risks to human water users, including canoeists and swimmers).

Habitat creation as a mitigation measure specifically related to the design of the weir is not always possible. Under such circumstances alternative mitigation measures should be considered that indirectly benefit the flora and fauna of the river and riparian zone.

A simple mitigation includes the use of neighbouring structures, such as a bridge or a building, for providing nesting boxes for dippers, flycatchers and wagtails. Backwaters

may be created in which fish can shelter during floods, or improved bankside planting to benefit invertebrates as well as to stabilise banks. Roosting sites for bats can be created in old buildings. Where there has been considerable loss of habitat through weir construction or modification and associated bank protection there may even be an opportunity to create a pond to the side of the stream and an associated marshland.

11.6.7 Monitoring

Post-construction and modification or removal of a structure should be carried out to identify the impacts of the changes imposed in a watercourse and floodplain. The data collected will also be used to evaluate the effectiveness of the mitigation measures in place. The monitoring programme may include the following surveys:

- phase 1 habitat survey of floodplain habitats
- river habitat surveys and mesohabitat surveys
- aquatic and marginal plants
- aquatic invertebrate (including white clawed crayfish)
- fish
- mammal and bird
- reptile and amphibian
- invasive species.

Hammond *et al* (2011) provides a set of procedures to develop a monitoring programme according to project size, complexity, risks associated with the measures, river type and available funds.

11.7 RECREATION AND NAVIGATION

With the decline of commercial river traffic on the UK's waterways, water-based activities are now dominated by leisure, which include rowing, sailing, motor boating, canoeing, and open water, marathon and triathlon swimming. Designers are urged to consult the relevant sporting bodies to find out how the river is currently used and what specific requirements need to be accommodated in the proposed works. In addition, the importance of the contribution that the weir makes to the riverscape for the enjoyment of land-based activities adjacent to the river, and for overall visual amenity, may be influenced by proposed works to modify or remove a weir structure. Rivers are an important visual amenity, particularly in the urban environment. Paths by rivers offer green transport routes. Safe access should be considered as the noise and visual interest created by the tumbling water over the weir can attract people.

The main limitations to recreation near to weirs are associated with safety and water quality as discussed in **Chapter 10 and Section 11.4**. Substantial weirs with powerful flows of water may be prone to having undertows. In addition, water quality is compromised through the extensive use of rivers for regulated disposal of treated wastewater and other effluents including road runoff and industrial discharges. Safety interests for all sports relate to the provision of suitable access from water to land.

11.7.1 Navigation

Weirs for navigation regulate water levels in an upstream impoundment to allow the navigation of vessels over a range of flows. Typically, navigation locks are provided either on the main channel or an associated cut, permitting traffic to pass upstream and downstream of the weir. If the locks are operated efficiently, the weir should ensure that a minimum depth is maintained upstream to permit the navigation of vessels.

In England and Wales, the statutory bodies managing navigation on inland waterways include the Environment Agency, Canal & Rivers Trust and the Broads Authority with some smaller authorities. These navigation authorities are granted powers by an Act of Parliament and so have statutory rights. Navigation authority consent is generally required before doing anything that obstructs or interferes with navigation (see **Section 9.3.3**).

Other organisations to consider are any trade associations such as the Thames Boating Trades Association (TBTA) and recreational associations (see Ackers *et al*, 2009). Consideration should be given to timing of works on weirs when navigation is at its lowest. The preferable period for works is during the summer while flows are at their lowest and daylight working hours longest. However, it is also the time of the year when navigable rivers are at their busiest, predominantly with leisure craft.

11.7.2 Water-based recreation

Weirs can present a barrier to free movement of boating craft and create safety issues associated with

currents downstream of structures. Provision of suitable access to and from the water, slipways, canoe portages and boat access may need to be considered.

Canoeists on UK rivers may experience the placid waters of a canalised river and naturally faster flowing, more challenging stretches. However, weirs can offer the faster flowing conditions that some canoeists seek as part of the engineered infrastructure of canalised rivers. These challenging conditions inevitably involve some risk, but properly engineered, the risks can be reduced without losing the excitement. More detailed guidance is available from British Canoeing (see **Websites**).

Websites

British Canoeing: **www.britishcanoeing.org.uk**

GB NNSS: **www.nonnativespecies.org/home/index.cfm**

Magic website: **http://magic.defra.gov.uk**

National trails: **www.nationaltrail.co.uk**

Ramblers Association: **www.ramblers.org.uk**

Sustrans: **www.sustrans.org.uk**

Weirs and sluices are often attractive structures for canoeists, but can be hazardous. Particular problems are experienced with weirs that have a steep downstream face and submerged hydraulic jump. This can result in hydraulic conditions that trap a swimmer or a canoeist underwater in the reverse roller downstream of the weir. Particular care is needed to avoid such conditions when designing new weirs or rehabilitating existing structures. This issue is discussed in more detail in **Chapter 10**.

11.7.3 Angling

Angling is a very popular sport, bringing revenue for private river owners, and is an important business for some country estates. The banks of many main river tributaries are rented to angling clubs. Weir pools can be particularly popular fishing spots (see Environment Agency, 2013a). When considering structures on these banks, consultation with the relevant clubs, businesses and users is vital. This may include consideration of whether access is to be either encouraged to promote angling access or discouraged to reduce poaching opportunities.

Maintenance and construction works carried out in rivers can be very disruptive to angling. So it is crucial that the timing of such works avoids periods of heavy angling activity (eg competitions). Angling clubs should be advised well in advance of the works being executed.

11.7.4 Land-based recreation

The enjoyment of water also comes from the use of riverside public rights of way, which may include access along as well as crossing over the river, often using weir superstructures. Organisations to contact include LAs and national organisations such as Sustrans, the Ramblers Association and National Trails (see **Websites**).

The CRoW Act 2000 gives public access to large areas of the countryside. This means that there may be public access in the area, even though no public right of way is designated. These ‘open access land’ areas are shown on the Magic website (see **Websites**) or on current editions of 1:25 000 Ordnance Survey (OS) maps.

To temporarily divert or close a public right of way will require permission from the LA in a similar process to planning permission. This must be applied for about eight weeks before the closure is required to allow for public consultation by the LPA. Applications for permanent closures must be agreed by the SoS and would need to be accommodated in the overall programme of the works as these applications take longer.

During construction, the LA will require that the temporarily re-routed footpath is advertised and well signed for the duration of the works. Consideration of materials and routing should be sensitive to the surrounding landscape.

Footbridges across rivers often carry national trails and are important for amenity.

Rivers are an important visual amenity, particularly in the urban environment. Paths by rivers offer opportunities for green infrastructure accommodating non-motorised transport routes to access shops and employment away from major highways. Weirs may provide an attractive destination point along the river where angling or feeding the ducks is an important leisure activity, so appropriate platforms with provision for wheelchairs and pushchairs should be considered. In parks and public places, this could be extended to the provision of benches and picnic tables, as long as these are positioned where it is safe for the public to go, and spaces for wheelchairs are provided near seats.

11.7.5 Access arrangements

The requirements for the provision of reasonable access, which do not discriminate, is a legal obligation placed on public bodies under the Disability Discrimination Act 1995 and the Equality Act 2010. Guidance by the Environment Agency (2012) sets out comprehensive design standards for pond dipping platforms, boardwalks, handrails and paths to facilitate access to the river environment.

When public access is proposed over or near a weir, a public safety risk assessment should be carried out and appropriate measures should be provided to minimise the risk to the public (edge protection, security, machine guarding etc). Access should also consider provision for portage around the weir, the ease of self-recovery from the water and access for the emergency services.

11.8 HISTORIC ENVIRONMENT

Weirs have formed part of water management systems in the UK since at least the Roman period, and the weir structures that exist today can have historic significance for a number of reasons. Identifying the heritage significance of a weir at an early stage in a project will ensure that statutory designations are recognised, consent requirements met, and harm to the historic environment is kept to a minimum. Often, weirs form one element of the much wider historic landscape, be it a designed landscape or an industrial complex, and without considering this wider context at the start, the heritage significance of a weir cannot be fully understood.

Weirs take many forms, serve many and multiple functions, and so have not lent themselves to any coherent classification or study. Until recently, the perceived threat to historic weirs has been low. However, recent changes to domestic and European legislation, including the WFD, have led to the adaptation and removal of weirs, with an increased interest in hydroelectric schemes that has also involved the adaptation of historic weirs.

Historic water management assets were considered by English Heritage (now Historic England) as part of the NHPP, and an objective to improve understanding of weirs and their significance, forms part of a strategy for water and wetland heritage (see English Heritage, 2011, Heathcote, 2012, Firth, 2014).

11.8.1 Heritage significance

In preparing proposals for the maintenance, modification or removal of weirs, it is advisable to consider the cultural heritage significance of the weir and its surroundings at an early stage. This will allow potential impact on the historic environment to be assessed, and inform any decisions that may arise from possible conflicts, such as between the cultural and natural heritage of a site.

Weirs can have significance as heritage assets for one or more of the following reasons:

- The weir structure has historic significance, for architectural, historic or technological reasons. It could be a good example of a particular architectural style or tradition, a rare survival of a historic form of technology, or may have been designed by or for a notable individual.
- The weir preserves elements of earlier structures. This may be represented by several phases of construction visible in the structural fabric, or by the presence of earlier elements, for example waterlogged timbers, concealed beneath or within the existing weir.
- The weir forms part of a water management system for a historic building or complex, such as a mill or lock. This can be for a working, surviving mill, or the weir may be one of the few surviving features of a complex that has been removed, or represented only by below-ground remains.
- The weir forms part of a designed landscape, as an architectural feature, by impounding water that forms an important element in the design, or by altering the quality of water as it flows through a landscape (eg Studley Royal).
- The weir or the water that it impounds contributes to the setting of a heritage asset.
- The impounded water preserves waterlogged archaeological remains that would otherwise not be preserved.
- The weir or the water that it impounds contributes to the aesthetic value of a historic landscape, through visual impact or, in some cases, the sound that the water creates.
- The method of operating the weir is of importance.

11.8.2 Heritage assessment

Early assessment of heritage significance indicates that harm to the historic environment should be minimised. A programme of further evaluation or mitigation can then be agreed with the relevant statutory bodies (Historic England, Historic Scotland, CADW or NIEHS), the LPA archaeologist or conservation officer as appropriate. This may include a pre-intervention record being made of the extant structures, archaeological investigation, or a watching brief maintained during any works.

It is important that the assessment procedure is robust and clear enough for the potential harm to heritage assets and the historic environment to be weighed against the benefits of undertaking the proposed works. It may be the case that the heritage significance of a weir structure precludes full compliance with the WFD and eel regulations, or that major changes to design are required to allow sensitive structures to be retained.

It is advisable to include a heritage expert in the design process, to ensure that statutory requirements are met, and to minimise harm to the historic environment. Ackers *et al* (2009) sets out a five-stage process for heritage assessment which can be applied specifically to activities associated with weirs. For certain weir assets, the time required for heritage assessment can be significant and should not be underestimated in the planning phases of the project.

11.8.3 Heritage designations

Weirs that have the greatest heritage significance may be protected as 'designated heritage assets' as Scheduled Monuments, listed buildings, or may fall within wider designations such as registered parks and gardens, World Heritage Sites (WHS) or Conservation Areas. If a weir is designated then consents may need to be obtained for works. Note that it is possible the designations will represent a major constraint to intended proposals and so again it is important to seek advice from statutory bodies and the LPA early on.

If a weir or its surroundings are protected as a designated heritage asset the NPPF states that significance can be harmed by alteration to it or development in its setting. The NPPF states that any significant harm requires 'clear and convincing justification' and that substantial harm or loss should be exceptional, or in the case of the highest level of designations, wholly exceptional (DCLG, 2012). This applies to activities requiring planning consent, but good practice should apply these policies where planning consent is not required. Specific consents would still be required for works that will affect listed buildings, Scheduled Monuments or Conservation Areas (see **Section 11.8.4**). Any works would need to be sympathetic to the heritage significance of the structure and its context, and it is likely that a programme of archaeological recording and mitigation would be required. Consult Historic England and the LA at the start.

Most weirs are not designated, but this should not be taken as an indication that they are not of heritage value. There are many cases where weirs are integral to the setting and legibility of historic structures and landscapes, but have not received statutory protection. In particular are instances where mills are protected as listed buildings, but the weirs that provide the flow of water to power the wheels are not designated. Weirs are located at strategic points on a watercourse and are unlikely to be relocated during their period of use. They are often subject to repair and consolidation, rather than replacement, and so surviving weirs can have the potential to retain early fabric.

Paragraph 128 of DCLG (2012) requires that applicants for planning permission should describe the significance of any heritage assets affected, including contribution made by their setting. Where a site on which development is proposed includes or has the potential to include heritage assets of archaeological interest, LPAs should require developer to submit an appropriate desk-based assessment and, where necessary, a field evaluation. Paragraph 135 also states that when considering applications that affect directly or indirectly non-designated heritage assets, a balanced view will be required having regard to the scale of any harm or loss and the significance of the heritage asset.

11.8.4 Procedure

The following recommended procedure broadly follows Ackers *et al* (2009). These stages represent a framework for assessment and mitigation, but the requirements of individual sites will be varied and diverse, so the approach to heritage should be tailored to suit each project.

Inception

As previously noted and in **Chapter 6**, it is important to confirm from the start the designations that apply to the weir and associated structures. It is recommended that the LA archaeologist and HER are consulted at an early stage in any weir modification scheme. If a weir is designated or forms part of the setting of a designated heritage asset, then the LA conservation officer, LA archaeologist and the relevant statutory body should be consulted. If the modification has the potential to cause erosion, flooding or drainage of a Scheduled Monument then Historic England or the relevant statutory body must be consulted.

The necessary permissions will need to be sought, eg listed building or Scheduled Monument consent may be required. If a structure is to be removed within a conservation area, then Conservation Area consent will be required.

Assessment and approvals

A desk-based historic environment assessment should be prepared by a heritage expert to identify at a minimum:

- The known heritage significance of the weir structure, including an understanding of its date, development and function.
- Designated and non-designated heritage assets within the immediate area, their significance and any contribution made by the weir or the water that it impounds to that significance.
- The impact of proposed options for the weir on the significance of heritage assets within the area.
- The potential impact of proposed options on the survival and stability of below-ground archaeological deposits or historic structures, through altering water levels in the local water table.
- Recommendations for further investigation required to establish heritage significance, and identification of any necessary consents.
- Recommendations for mitigation.
- Liaison with statutory authorities and planning bodies.

Good practice guidelines are set out by the Chartered Institute for Archaeologists (CIfA) (2014) and Historic England (2015).

Further investigation may be needed if the heritage significance or archaeological potential of a site are not fully understood. Archaeological evaluation and excavation can be used to assess the survival and significance of below-ground remains that may have been associated with a weir, and which may be affected by proposed works. For example, the structural remains of associated mills, lock houses, leats, sluices, or other water management features may survive close to the weirs that formerly served them. Assessment of the structure may also reveal more about its date, historic function and significance. The materials used in the construction of historic weirs will vary significantly, being timber-framed, masonry, or a combination of the two, as will the design. Weirs may employ a range of technologies, and may be more or less decorative depending on their function and setting. If a weir structure, or the water that it impounds, has the potential to preserve earlier historic remains, then underwater investigation may be required. For example, at Iffley Lock the waterlogged remains of an earlier timber lock were identified by diving.

Once a preferred option has been selected, a heritage professional can assist in obtaining the necessary heritage consents and agreeing a programme of mitigation.

Detailed design

Informed by the assessment, appropriate mitigation can be designed to minimise harm to heritage assets and the historic environment. This may include:

- **Mitigation by design.** Examples might include reducing visual impact on the setting of heritage assets by using suitable building materials or methods, or maintaining a water level or flow that serves a historic water mill. In some cases, elements of a historic weir have been preserved in the river-bank to retain some legibility of a historic feature, but removing the barrier to fish movement.
- **Mitigation by record.** If the need to modify or remove a weir structure is deemed to outweigh its heritage value, then the structure can be preserved by record. The level of recording will depend on the significance of the structure, but might include photography, written records or measured survey.

If works will affect designated heritage assets, then some mitigation measures may form part of the conditions of consent, and these must be adhered to.

Construction

It may be necessary for an archaeologist to carry out intermittent site visits or undertake continuous monitoring (and/or archaeological supervision and recording) during construction phases, to record any features of heritage significance that may be encountered during the works. The watching brief may involve the recording of earlier phases of structural remains identified during the removal of structures, or the presence of waterlogged remains within the impounded water. If remains of national significance are encountered, the LA archaeologist and relevant statutory authority should be consulted to decide a course of action.

Maintenance, management and interpretation

The results of any recording work or investigation should be deposited with the appropriate HER, maintained so that the results are accessible. They may also be disseminated online via OASIS (see **Websites**). If any findings are of significance, they should be published in an appropriate local or national journal, and if deemed to be of sufficient interest to the public, it may be appropriate to provide onsite signage.

Websites

OASIS: **http://oasis.ac.uk/pages/wiki/Main**

11.9 LANDSCAPE AND VISUAL IMPACT

11.9.1 Landscape character

The European Landscape Convention defines landscape as an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors (Council of Europe, 2000). The convention sets out that the landscape is an important part of the quality of life for people everywhere – in urban areas and in the countryside, in degraded areas as well as in areas of high quality, and in areas recognised as being of outstanding beauty as well as everyday areas. The emphasis is that all landscapes are valued, whether designated or not.

A respect for the visual quality of a weir and its river setting is embraced in the Environment Agency's duty to conserve and enhance the natural beauty and amenity as discussed in **Section 9.4**.

This interaction between natural and human factors includes the influence of geology, soils, topography, land cover, hydrology, historic and cultural development, and climatic considerations (Tudor, 2014). The combination of characteristics arising from these physical and socio-economic influences, and their often complex interrelationships, makes one landscape different from another.

Weirs associated with water mills have been in existence since Roman times and the Domesday Book recorded over 5500 sites, which can add to the richness of the riverine landscape. Building materials in older properties and vegetation assemblages often reflect the local variation in geology and soils, all of which contribute to define the local landscape character. All these heritage areas are subject to different designations and consenting regimes, as discussed in more detail in **Chapter 9**. These elements are part of the national heritage and cannot be replaced.

Landscape characteristics are a complex interrelationship between natural and human influences and the appearance of that landscape provokes subjective responses in people. One group of people might consider a landscape to be a beautiful countryside idyll, whereas another group may view it as 'uninspiring' agricultural scenery. Peoples' responses are also related to the location and the value that they place on a particular landscape. Commercially, any property near a river has a premium value and local residents are often very protective of their environment.

The noise and visual appearance of tumbling water over a weir can attract people and in some cases the added interest of the structure (although some may not be visually attractive). Works involving existing weirs frequently combine heritage and landscape issues, as many weirs are associated with industrial heritage sites, mills, historic parks and gardens, and protected landscapes. Heritage issues are discussed in **Section 11.8**, and the interrelationship between landscape and heritage issues needs to be understood. Important or protected views may be defined in local planning documents. Analysis of the effects of the proposed works may include the setting of a heritage asset as well as the perceived change in the quality of the view.

Table 11.2 Landscape issues to consider at different stages of a river scheme (after Ackers et al, 2009)

Development stage	Landscape issues
Data gathering	Identifying major landscape designations such as national parks and AONB, and areas of public access including along public rights of way (PRoW), access land under the CRoW Act 2000 or common land designation. Reporting on their potential implications.
Assessment and approvals	Landscape character assessment and landscape visual impact assessment to inform the assessment of options and to feed into EIA procedures. Outline design proposals sufficient to allow negotiation with, and applications to, consenting authorities.
Detailed design	Landscape proposals for mitigation and enhancement works. Such works can include hard materials like wall cladding and paving works. Soft works include tree and shrub planting, garden and land reinstatement, seeding and habitat creation.
Construction	Site inspection and monitoring of construction impacts on trees and other protected landscape features. Ensure that the landscape impact of any site changes can be assessed and mitigated if required.
Maintenance	On completion of the main engineering works, a maintenance period is required for landscape planting works. Industry good practice is to implement over a minimum of three full growing seasons. This gives the best chance of successful establishment. Management is the process by which the design intent of the landscape works is delivered. Maintenance activities are the activities that are undertaken to achieve the management objectives.

11.9.2 Scheme implementation

The process of delivering an in-channel scheme is set out in **Table 11.2**. This summarises the typical landscape matters at each stage and the level of detail required. This is not intended to be exhaustive and careful review is required to reflect the characteristics of individual sites.

11.9.3 Assessment

In the evidence gathering stage, using existing landscape character assessments will provide information on the elements that create the local character. This may include the English National Character Areas (NCA), the regional landscape character areas in Wales, county level landscape character assessments (LCA) including the suite of Scottish LCAs – district level assessments, and local LCAs (Tudor, 2014). The DOENI also publishes landscape character areas covering all of Northern Ireland.

Policies, other statements and evidence in public documents such as statutory development plans, strategies and associated documents will provide information on current designations including those relating to landscape, historic and marine environment, biodiversity and geodiversity. A review of designations, within and adjacent to the area of study, will be needed. It will be important to ascertain reasons for the designation and any special qualities, such as concerning an AONB. Relevant information will be available in citations, management plans, and designation histories.

Information may be available on heritage assets and protected conservation sites (eg SPA and Sites of Specific Scientific Interest [SSSI]) and notable species as discussed elsewhere in this chapter.

The project may need a landscape and visual impact assessment (LVIA) to be carried out to support an application for planning, other approvals or as part of an EIA. The published LCA information will help to inform these documents, but more detailed characterisation may be required at an appropriate scale for the proposed project. The LCA informs the project team:

- what is valuable in landscape terms
- what should be retained and ideally enhanced
- what drivers for visual change exist within the landscape
- its particular vulnerability to different types of development.

11.9.4 Design

Reviewing the requirements and design aims of a proposed scheme may allow the adoption of a natural flood management (NFM) concept. The intention of the NFM concept is to re-connect a river with its floodplain through the incorporation of generous buffer zones or wider marginal areas, or through the allocation of lands suitable for periodic flooding. The strategies within the NFM often lead to improvements in the river habitat and ecology. For example, the introduction of wider river channels to accommodate seasonal high flow rates will provide a valuable marginal habitat when the river is at its normal height. Tree planting can stabilise embankments and to reduce the movement of sediment in floodplains.

The creation of space for water through a diverse range of strategies including tree planting, creating generous buffer zones along all watercourses and removing raised flood banks where possible affords the opportunity to re-connect rivers to their floodplains and enhance the river landscape ecological value. 'Natural' weirs created through the placement (or allowing the retention of) large pieces of wood can provide morphological diversity, localised flow diversity and areas of refuge within the channel.

Wood accumulations (also known as large wood) affect the geomorphic processes of a river system, which can affect sediment storage and routing, stream bed and bank structure, velocity distributions, and sinuosity of a stream. Further detail can be found in Environment Agency (2013b).

The catalyst for the removal of weirs to allow the river channels to be 'naturalised' through the implementation of the WFD, offers opportunities to realise dual benefits for landscape amenity and ecological value. To achieve 'good' status for waterbodies in terms of biological, physio-chemical, chemical and hydro-morphology, offers opportunities to realise dual benefits for landscape amenity and ecological value. However, the potential effects on the landscape also need to be considered. For example, removal of a weir may isolate the river from its floodplain where historic deepening and widening of the river channel has been undertaken. This may reduce the visibility of the river or waterbody in the landscape and the water table may be lowered in adjacent habitats. This could change the overall vegetation composition through adaptation to drier conditions, again potentially changing the landscape character which may be designated or protected. Careful design and morphological restoration of the channel alongside weir removal would need to be considered (see **Chapter 12**).

Bridges are perhaps one of the most visually important structures on rivers – some have long been listed and protected. Weirs may be perceived as a close second in importance on the river scene. A number are equally historic and some, such as the medieval mill weir below Warwick Castle, form an integral part of important listed landscapes. The drama of falling water has been exploited by landscape designers from earliest times, from the makers of Moghul gardens to the English eighteenth century landscape school. Occasionally there have been inspiring modern weirs, such as the weir below Pulteney Bridge in Bath designed by Sir Hugh Casson. When building a new weir, the opportunity to make something 'spectacular' is seldom considered or budgeted for. When repairing a historic structure, sensitive use of materials and high-quality workmanship are required to avoid adversely affecting the structure and its appearance. It is recommended that an architect or landscape architect is involved in design or repair of all weirs of reasonable size.

A respect for the visual quality of a weir and its river setting is embraced in the Environment Agency's duty to conserve and enhance the natural beauty and amenity. Despite the design work and below-ground engineering, it is the finishes and detailing of the above ground elements of the structure etc that the public will be aware of. The following specific issues should be considered for new structures and modifications or repair of existing structures:

- **Scale.** The structure should fit comfortably into the river setting. It can be dramatic, but over-dominant structures such as bridges and gantries should be minimised.
- **Plan.** A weir does not always have to take a right angle route from bank to bank. A diagonal or curved weir is often attractive (subject to safe access), for example Casson's famous weir at Bath curves across the river at a deliberately oblique angle from the bank.
- **Materials.** In terms of cost and construction, concrete and steel may often be necessary, but especially when repairing old weirs built of other materials, brick facing or stone copings to concrete walls should be considered (see **Section 1.4.4**). Timber can also be used to mask the cruder features of some modern weirs. When concrete is adopted it should be used imaginatively to achieve variety in appearance and finishes. Advice from specialist suppliers and contractors should be sought during the design development taking examples from the architecture and structural engineering sectors as appropriate.
- **Clutter.** Associated fencing, signs, operational buildings, lighting, bank protection, certain kinds of fish pass and access roads all need to be considered in relation to the overall design. Where there are steep banks near public areas, planting suitable hedging or thorns is often an effective alternative to fencing, acting as a deterrent rather than a solid barrier.

11.9.5 Construction activities

Timing of construction works for landscape issues are generally less seasonally sensitive than other areas such as ecology or angling and navigation. However, restricted access to valued landscapes through closure of PRoW will need to be considered during the project planning stage.

The protection of existing valued features and elements should be managed through the implementation of a construction management plan addressing issues raised in the approvals documents submitted during the design stage. This should set out the key sensitivities and how these will be managed during construction. It may include, for example, protection of existing trees through the implementation of good practice guidance set out in BS 5873:2012.

11.9.6 Maintenance

On completion of the main engineering works, a maintenance period is required for landscape planting works. Industry good practice is to carry out the works over a minimum of three full growing seasons. This gives the best chance of successful establishment. Further information on typical considerations for planting can be found in Department for Transport (DfT) (2001).

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12 Geomorphology

12.1 INTRODUCTION

This chapter provides an overview of geomorphology as a discipline and why it is an important consideration when determining appropriate management measures for weirs. In many cases weirs affect geomorphological processes within rivers because of their impounding influence, the degree of which is dependent on factors such as the type of river, size, location and orientation and how long the weir has been present.

Geomorphological assessment methods are outlined, which will provide a useful resource for weir managers when planning and designing works (**Section 12.3**). An introduction to river types in the UK also demonstrates how rivers can respond differently to weir new-build, modification or removal and should be determined as part of a geomorphological assessment (**Section 12.4**). Geomorphological design considerations are described to ensure weir schemes are sustainable across all spatial and temporal scales (**Section 12.5**). Lastly, consideration should be given to the presence of contaminated sediment (**Section 12.6**) and the risk of its release downstream, and subsequent impacts on habitat following lowering, part removal or full removal of the weir.

12.2 WHAT IS GEOMORPHOLOGY?

12.2.1 The relationship between flow and sediment

Geomorphology, also known as fluvial geomorphology and hydromorphology, links channel forms and processes to channel flow, recognising the importance of the erosion, transportation and deposition of sediment in combination with the flow regime. This allows a full understanding of river dynamics, how processes are currently operating and how they could respond to change (both natural and artificial). It recognises that rivers are dynamic systems that change considerably over space and time and respond differently to different controls, including climatic, geological, land use and human activity. It also ensures that local scale processes are set within the wider context of the whole catchment. Through an understanding of river geomorphology, links can be made to river habitat and ecological response to certain conditions, recognising that geomorphology and ecology are fundamentally linked.

The relationship between flow and sediment within a river system produces local morphological forms and habitat at a particular point within the river system. Various descriptors attempt to define river geomorphology, in terms of river forms (eg meanders, point bar, transverse bar), river processes (eg erosion, transport, deposition, turbulence) and hydraulic habitat (eg riffle, pool, unbroken standing wave, chute), which can help to inform condition and river type (see **Section 12.4**).

12.2.2 Effects of weirs on river geomorphology

Weirs influence river geomorphology in various ways and the degree of impact is dependent on, among other things, the type of river, size, location and orientation, type of weir and how long the weir has been present. The impacts include (**Figure 12.1**):

- Causing an impoundment zone upstream of a weir providing low-energy flow conditions.
- Interruption to the sediment transport regime through deposition of sediment, particularly fine material, within the impoundment zone creating over-simplified habitat diversity. This can constrain downstream reaches of sediment reliant on upstream supply creating an unnatural morphology within the impoundment zone (particularly through formation of fine sediment features).
- Increased water levels, depths and flow widths upstream of the weir.
- Reduced flow velocities upstream.
- Moderated flow regime to downstream reaches.
- Modification to floodplain wetting frequency.

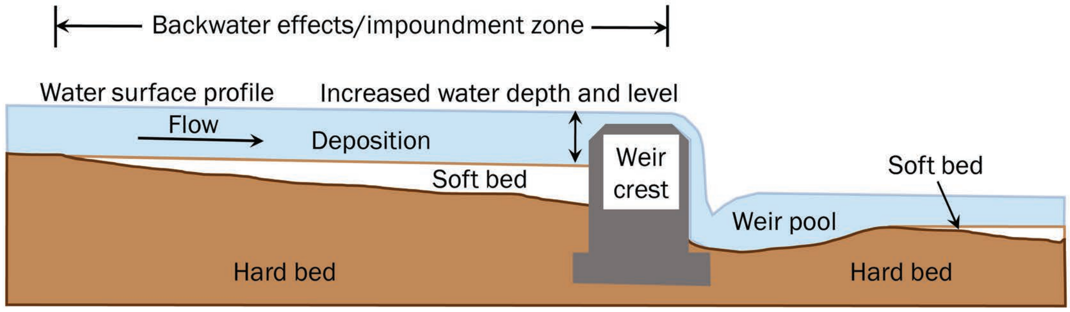

Figure 12.1 Impact of a weir on river hydraulics

12.3 GEOMORPHOLOGICAL ASSESSMENT

Geomorphological assessments are critical to weir management projects and a geomorphologist should form part of the core design team. The potential response of a river to a weir modification, removal or construction needs to be assessed appropriately and using appropriate technique to ensure that this response is predicted and quantified across the scheme design life.

12.3.1 River typology

It is important to have an understanding of the river type when assessing the potential effects of the installation of a new weir, or modification or the feasibility of removal. This should be undertaken by an expert geomorphologist as part of a suitable geomorphological assessment. This is because different river types have different flow and sediment characteristics. **Figure 12.2** provides a summary of the various UK river types and their associated characteristics that can be used to assess the degree of reaction to weir modification, new-build or removal. The resistance and reactivity of a river describes how robust the river type might be to removal in terms of geomorphological response.

Table 12.1 provides further detail of the key river types encountered in the UK, their characteristic forms and processes, potential impacts of weirs and sensitivity to weir modification.

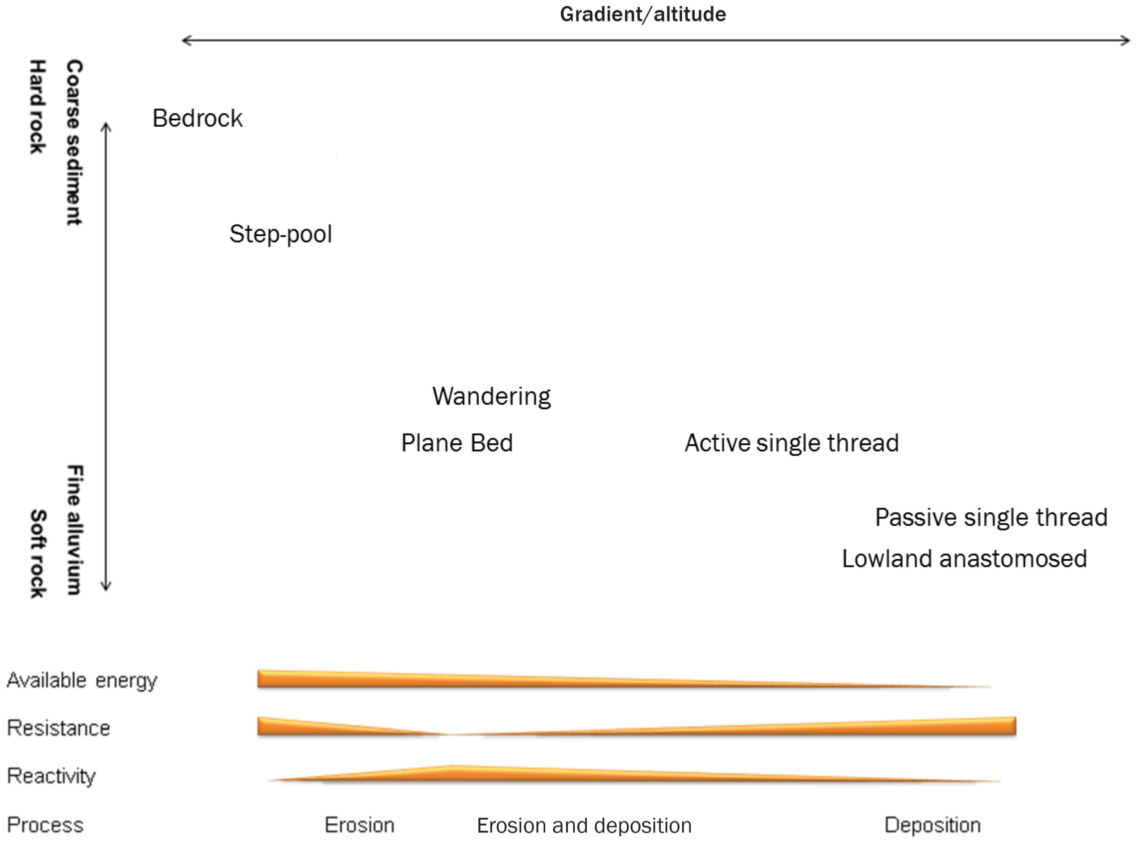

Figure 12.2 River types linked to geomorphological processes and response potential

Some rivers are more energetic than others and are likely to respond to weir removal more significantly than lower energy rivers, although this is not to say there will not be some reaction in low energy systems. Indeed, some weirs can influence river processes a long way upstream of the weir in low gradient rivers and water level lowering would occur immediately after removal or modification. Morphological change is likely to take a lot longer in lower energy systems compared to higher energy ones where changes are likely to occur over a shorter time span and perhaps a shorter distance upstream. With this understanding of river typology, the proposed works can be aligned to the characteristic natural processes.

When considering the type of river that is being assessed, it is important to determine whether the river is currently managed to a degree that artificially places it as a specific river type and whether under natural conditions (ie unconstrained or restored) it would take another form. For instance, a river may appear to be relatively passive as a result of a weir or series of weir structures that when modified will introduce active river processes and characteristics.

River type may change along a watercourse. This change may not be a smooth transition or a sudden change between types and it may exhibit characteristics of the different river types at certain points. So, expert geomorphological assessment is a necessity, as part of an audit of the river when considering modification weir schemes, when determining the river type and appropriateness of a mitigation measure. Inappropriate application of the typology may lead to the selection of measures that are unsuitable and ineffective or could lead to further deterioration of the watercourse. For example, the risks associated with removal of a weir in a bedrock system are lower from a geomorphological response perspective as the weir is likely to be located in a confined valley where bedrock presence in the valley margins would prevent lateral erosion of the river-banks.

12.3.2 Condition assessment

Numerous methods and techniques are employed by geomorphologists to understand river forms and processes, and river types across a variety of spatial and temporal scales. All of these techniques can potentially be employed to assess the geomorphological impacts of weirs on a river system. These assessments should identify the risks associated to building, removing or modifying the weir. They should be undertaken by an expert geomorphologist and should be undertaken as part of the design phase for weir build, modification or removal schemes. The type of assessment and level of detail will be determined by the level of risk associated with the scheme. The level of potential risk is often identified as part of an initial site walkover. The most relevant of the techniques available are summarised in **Table 12.2**. Further information regarding geomorphological assessment techniques is provided in Dangerfield and Leggett (2009).

Table 12.1 ***Geomorphological impacts of weirs and weir modification associated to river types (from Bentley et al, 2014)***

River type	Forms and processes	Impacts of weirs	Sensitivity to weir modification
Bedrock 	Significant bedrock within the channel and the floodplain indicates a very stable river type. Most common in upland areas and contains little stored sediment on the channel bed, aside from temporary stores of fine sediment deposited in pools. The channel gradient is likely to be steep and they often exist within confined valleys, giving energetic flow conditions able to transport large amounts of sediment.	Dependent on size of weir. Large weirs could disrupt sediment continuity to downstream reaches that could have implications for downstream geomorphological condition and stability due to sediment starvation (if located in a reach where bedrock presence is limited).	Unlikely to result in significant changes in geomorphological features and processes upstream. There may be a short-term release of sediment stored behind the weir due to weir crest lowering. However, modification can reinstate natural sediment transport processes which could lead to recovery of gravel bed reaches further downstream that are reliant on this supply.
Step-pool 	Generally formed by boulder groups, or cluster or bedrock layers forming steps separated by pools, providing stable channel conditions. The pools may contain finer sediments due to the low-energy conditions created by the backwater effects of the steps. These may be transported downstream during elevated flow conditions. The channel gradient is likely to be steep and the river usually flows through a confined valley, giving energetic flow conditions able to transport large amounts of sediment. They are often found in upland areas. Only larger material is generally stored on the channel bed.	Dependent on size of weir. Large weirs could disrupt sediment continuity to downstream reaches within step-pool reaches, which could have implications for downstream geomorphological condition and stability. High head hydropower schemes are often located on step-pool rivers and the associated flow depletion can result in elevated sediment deposition within the depleted reach that reduces sediment transport downstream.	Unlikely to result in significant changes in geomorphological features and processes upstream. There may be a short-term release of sediment stored behind the weir due to weir crest lowering. However, modification can reinstate natural sediment transport processes which could lead to recovery of gravel bed reaches further downstream that are reliant on this supply.

River type	Forms and processes	Impacts of weirs	Sensitivity to weir modification
Plane bed 	Generally dominated by cobbles and gravels, but significant depositional features are not present with a monotonous riffle or run biotope dominating with few or no deeper pool areas. Moderate gradient and with restricted connectivity to floodplain or confined or partly confined valleys. Sediment transport capacity is relatively high and lateral activity is often restricted by stable banks. Little fine sediment infilling of the channel bed. Hydromorphological characteristics (shallow flow depth, riffle flow type, few sediment features, gravel or cobble bed) mean that under natural conditions, the channel bed is likely to be uniform. Can be artificially created as a result of modification or straightening of a river (particularly in urban areas).	Weirs can create unnaturally low stream power levels behind the weir within the impoundment zone and higher depths than would be expected for this river type. This could lead to choking of the gravel or cobble bed with fine sediment as a result of the dampened flow conditions.	Weir crest lowering is likely to help reinstate the natural processes associated to plane bed systems and allow recovery of the gravel or cobble bed by creating shallower flow depths compared to the flow width.
Wandering 	Often found in moderate gradient systems where sediment loads are high with an extended or wide valley floor. Display some braided and active single thread channel characteristics, but are highly responsive and dynamic rivers. Lateral movement can be significant where banks are weak and riparian vegetation is sparse, resulting in channel switching as it migrates across the valley floor. Depositional gravel features are often large (because of the high sediment loads and capacity for lateral movement). These rivers have often been heavily managed with walls and gravel removal, meaning that it is rarer than would be expected naturally.	Create dampened flow conditions within the impoundment zone, reducing lateral activity potential and increasing the potential for fine sediment deposition. Also reduces the sediment transport potential to downstream reaches that are reliant on this supply. Outflanking of weirs is most likely in wandering rivers due to their ability to erode laterally and building of a new weir in a wandering river may increase the risk of channel avulsion. See **Case study A2.3**.	Weir crest lowering would help to reinstate the natural hydraulic gradient and natural flow and sediment dynamics upstream as well as reconnecting to downstream reaches. The significant activity levels means there could be considerable lateral and/or vertical response because of weir modification, which should be carefully assessed.
Active single thread 	Generally, these are rivers with a lower gradient compared to wandering systems. Sediment loads are moderate and lateral movement can be moderate (depending on bank cohesivity and the condition of the riparian corridor). Depositional features are small to moderate in size (restricted by sediment loads and lower levels of lateral erosion). Usually found in unconfined or partly-confined valleys and are generally composed of gravels and finer sediment. Can typically erode, transport and deposit during channel forming flows.	Likely to be affected by the presence of weirs through the low-energy flow conditions created upstream leading to increased fine sediment deposition on the bed and a reduction in the lateral activity. It will also reduce sediment transport potential to downstream reaches. See **Appendices A3.2 and A3.5**.	Weir crest lowering would help to reinstate the natural hydraulic gradient and natural flow and sediment dynamics upstream as well as reconnecting to downstream reaches. The potential for upstream lateral erosion following modification would need to be considered due to the possible moderate lateral activity levels. Some bank collapse could be expected over a wide area (related to the length of impoundment and valley slope) as a short-term response to water level lowering and possible bed incision, which is linked to the bank material type and cohesion.

River type	Forms and processes	Impacts of weirs	Sensitivity to weir modification
Passive single thread 	Usually found in lowland areas with a low gradient. Sediment loads (particularly gravels) are lower and bed material is generally dominated by finer sediment (eg sands and silts). Depositional (gravel) features are uncommon or poorly developed if present. The banks of the channel are often cohesive restricting lateral movement. So any available energy is often focused on the channel bed, leading to incised, deep channels with a poor connection to the floodplain. Bank protection may be artificial creating passive conditions by restricting lateral movement potential.	Create excess fine sediment deposition in the upstream impoundment zone behind the weir. The impoundment length can also be significant because of the generally low gradients associated to these river types. Also, the potential response can be spatially extensive. Elevated water levels behind the weir can drown-out habitat diversity.	Removal, lowering or bypassing the weir would help to reinstate the natural gradient upstream and encourage transport of some of the fine sediment load. The risk of significant fine sediment release downstream, in the case of weir removal lowering or bypassing, would need to be considered as well as cohesive fine sediments behind the structure needing to be removed following weir modification. Water level lowering associated with removal or lowering upstream can lead to river-bank collapse, which is often a short-term response and stabilises over time. See **Appendix A3.4**.
Low energy anastomosed 	Found in lowland areas with low gradients (higher energy anastomosed systems exist in higher gradient, often upland areas, but are relatively rare in the UK). They develop a multi-thread channel network through stable islands, bars and berms due to the formation and movement of large wood. Floodplain connectivity is good and different channels are activated at different flow levels, spreading flow energy over a wide area. Bed material is generally composed of fine sediment with some gravel exposed in locally energetic areas. Wet woodland often thrives in the riparian zone of this type.	The low-energy flow conditions created upstream can lead to excess fine sediment deposition and disrupt sediment continuity and flow regime variability to downstream reaches.	Removing, lowering or bypassing the weir would help to reinstate the natural gradient upstream and encourage transport of some of the fine sediment load that will maintain a more diverse morphology through the reach.

Table 12.2 Geomorphological assessment techniques

Assessment technique	Description
Historic trend analysis (HTA)	Investigation of trends in geomorphological behaviour and habitat diversity over time and space using available historic maps and datasets. Improving aerial imagery quality, such as Google Earth™ and unmanned aerial vehicles (UAVs) (drones), has allowed forms and processes to be identified at a broad-scale and over time where older versions of imagery are available for comparison to current imagery. Useful for identifying when weirs were built in the past and how the river has reacted.
Biotope (hydraulic habitat) mapping	Detailed mapping of hydromorphological characteristics based on field observation to establish the key physical biotopes and hydromorphological features within the study area. With the improving quality of aerial imagery, particularly through the use of UAVs, it is envisaged that this data will also be used for this purpose in the near future. Useful for mapping lack of biotope diversity upstream of a weir and using this to infer how this may change following modification or removal.
Fluvial audit	Otherwise known as geomorphological or hydromorphological assessment, river reconnaissance and geomorphological audit, a fluvial audit is the establishment of baseline hydromorphological form and behaviour for a river reach in the context of conditions prevailing in the wider river network and catchment as a whole. It incorporates a range of techniques as well as the field survey (HTA, biotope mapping etc) and builds a conceptual model of river system functioning, and is employed at a variety of scales. It often includes some physical measurement of channel geometry, forms and sediment sizes. Useful for identifying detailed river form and process information linked to the impact of the weir and providing information on analogue sites outside of the influence of weirs to capture how the river may react to modification or removal.
Hydraulic modelling (numerical and process modelling)	Use of computer models to simulate physical processes over time and space. Hydraulic models take various forms, and provide varying accuracy dependent on the approach, so appreciation of the constraints associated with each potential method need to be fully understood before conclusions are made. Useful for modelling and determining hydrological impacts of the flow and sediment regimes under weir removal or modification scenarios. It can also be used to quantify changes to habitat.
Sediment survey	Determination of the physical and, in some cases, chemical characteristics of sediment in a waterbody. This is often undertaken to determine sediment size and mix information, linked to river processes, to determine the current sediment regime and the impacts that structures such as weirs are having on river bed characteristics and quality. Useful for identifying sediment characteristics up and downstream of the weir and how sediment transport is currently impacted.
Geodynamics assessment	Detailed assessment of the physical characteristics, dominant processes and morphological dynamics of a river system. This takes fluvial audit information and further quantifies process and form information through physical measurement using a variety of instrumentation such as erosion pins. It is expensive, but sometimes necessary when the risks associated to weir modification or removal and potential river response are high. Useful for further quantifying the potential change of the river system following removal where risks are very high.

12.3.3 Geomorphological monitoring

The monitoring of geomorphological processes, creating a baseline database or to appraising the response of a watercourse to a new, modified or removed weir is important, particularly if there are unquantified risks to infrastructure or habitat, eg bank erosion upstream following removal of the weir or release of fine sediment downstream.

There are simple and cost-effective methods of monitoring for establishing the geomorphological impacts of weir removal, modification, or constructing new weirs, which should be considered as part of the design phase. The monitoring period is dependent on the river type and how quickly it is likely to respond to imposed changes. The spatial scale of the monitoring should be related to the predicted zone where changes are likely to occur following implementation of the scheme. This would allow for any adaptive management requirements to be identified following implementation of the scheme. Methods include:

- **Fixed point photography:** photographs taken at a fixed point at regular time intervals or a time-lapsed camera to be fitted to the scheme to get continuous data (see Appendix A3.6). The photographs are then interpreted by an expert geomorphologist to determine river response. This is a cost-effective measure,

which should be used across the potential zone of predicted change to monitor wider system adjustment up and downstream, using a series of fixed points. However, it only monitors horizontal plan form changes and not bed form changes unless they are generally above the water surface.

- **Regular site walkovers or visits:** the detail and frequency of monitoring can be tailored to the affected area of the associated scheme and available budget. These are all likely to incorporate some form of photographic and descriptive record of river response both at the scheme and at a wider scale.
- **Biotope (hydraulic habitat) mapping:** this can be undertaken as part of site walkovers and records the diversity of flow types and hydraulic habitat within the potential impacted reaches. It can be compared to baseline data to determine response and improvement.
- **Sediment monitoring:** detailed measurements of sediment size and volumes to determine the effects on the sediment regime over a wide area.
- **Erosion and/or accretion monitoring:** installation of measuring instruments (such as bed or bank erosion pins or accretion mats) to monitor changes in erosion and deposition patterns over time. This requires investment in equipment and monitoring over a longer term.

The geomorphological impacts of weir removal projects, as well as new weir structures and weir modifications, suffer from a lack of monitoring data across the UK. This lack of data is associated with a general shortage of funding to monitor the impacts of new schemes with funding generally only available to implement the scheme. It also relies on having suitable baseline data, which is often lacking. The largest databases of case studies that have included a weir removal or modification element can be found on the RRC website (see **Boxes 12.1 and 12.2**), and also the European RESTORE or the REFORM websites (see **Websites**).

12.4 GEOMORPHOLOGICAL DESIGN

12.4.1 Overview

When undertaking projects to design new weirs, modify or remove them, it is important to ensure geomorphology is incorporated within the design team, using an expert geomorphologist, to ensure that river response to the weir option is fully understood and that the siting and design ensures minimal impacts to geomorphological forms and processes (for new-build and modification) and works with natural geomorphological processes where possible.

Websites
RESTORE: **www.ecrr.org**
REFORM: **http://wiki.reformrivers.eu/index.php/Main_Page**
River Restoration Centre: **www.therrc.co.uk**

Possible impacts of proposed weir schemes are described in **Sections 12.4.2 and 12.4.3**.

Often, the potential negative geomorphological consequences (over a range of spatial and temporal scales) of a weir scheme can be readily identified during the design phases of the scheme and the scheme can be adapted to remove, reduce or minimise these impacts. For example, morphological restoration of the channel upstream of the weir to be removed can help manage the potential increase in energy levels associated with removal of the weir.

Using a generic 'one size fits all' geomorphological design for weir modification schemes is poor practice. Geomorphological design for weir modifications needs to be carefully aligned to local fluvial conditions and processes, and the river type, to ensure they operate successfully and sustainably as part of the river system.

Further geomorphological design information for weir construction, modification and removal can be found in **Sections 5.3 and 12.2.2**, Elbourne *et al* (2013), SEPA (2015b) and NRW (in press).

12.4.2 Weir removal, lowering or failure

Weir removal, lowering or failure reduces water levels upstream, with potential lowering of groundwater levels and impacts on functions. There may be improved flow and habitat diversity upstream, improved gravel bed and habitat quality upstream and downstream, and a more natural flow regime. Increased flow energy may lead to erosion of the river bed and banks (**Figure 12.3**), and transport of sediment, with restoration of natural sediment transport processes to downstream reaches (**Figure 12.4**).

Box 12.1 Weir lowering on the River Calder, West Yorkshire

In 2010, Padiham Weir on the River Calder was lowered and infilling of the channel bed was undertaken using a series of boulders and gravels to manage the increase in hydraulic gradient and prevent erosion of the channel bed and bank. Localised bank protection works were installed to protect nearby infrastructure (Environment Agency, 2013).

Box 12.2 Weir removal, River Monnow, Monmouthshire

Kentchurch Weir on the River Monnow, owned by NRW (formerly Environment Agency Wales), located within a large private estate, was thought to be a modern reconstruction of an older weir and was in the process of breaching. It was decided to completely remove the weir rather than repair it, also addressing the adverse effect it was having on WFD objectives including fish migration. It took 18 months to remove the 2.6 m high weir, which allowed migratory fish to access spawning grounds in the 160 km of river upstream and natural morphological processes to operate. Flood risk implications, potential heritage value of the structure, risk of release of sediment downstream and geomorphological changes following removal all had to be considered (RRC, 2013).

Further case studies on weir removal, lowering or failure are given in **Appendices A3.2 to A3.9**.

The following aspects should be considered when designing a weir removal or lowering scheme, or considering allowing a weir to fail. These are summarised in **Figure 12.5**, which shows the river process interactions, and the possible implications following weir removal or collapse:

- Accelerated river-bank erosion and collapse related to increased lateral erosive processes or collapse of over-steepened banks because of water level lowering following removal of the structure. Consider nearby infrastructure and historic features that could be affected by these processes. However, erosion and transport of sediment is considered a natural process for many UK river types.
- Sediment released downstream could deposit and increase lateral erosion locally and could also increase flood risk depending on the volume of material deposited.
- Depending on the size of the weir and the hydrological characteristics of the river type, the removal of a weir could alter the magnitude and timing of low and high flows downstream.
- Changes to bankfull capacity, exposure of services buried in the upstream river bed, changes in the width-depth ratio and gradient of the channel upstream of the former weir, which will influence sediment transport processes. This is sometimes difficult to quantify without detailed assessments and determination of whether these are positive or negative impacts depends on the river type and local conditions.
- Reinstatement of natural geomorphological processes including vertical (erosion of the river bed) and lateral (erosion of the river-banks) physical processes.
- Removal of the impoundment zone upstream of the structure, encouraging transport of sediment rather than deposition, particularly of fine sediment that often chokes the gravel bed in many UK rivers.
- Improved morphological diversity upstream, often with gravel features forming over time or exposing vegetated islands and marsh zones within the former impoundment zone for some river types.

- Improved sediment continuity and transport to downstream reaches, particularly of gravel material, which could lead to geomorphological and habitat condition improvement downstream.
- Possible decreased localised flood water levels upstream of the weir remobilisations of contaminated sediments upstream of the weir.

Figure 12.3 Local bank collapse following weir removal on the River Irwell

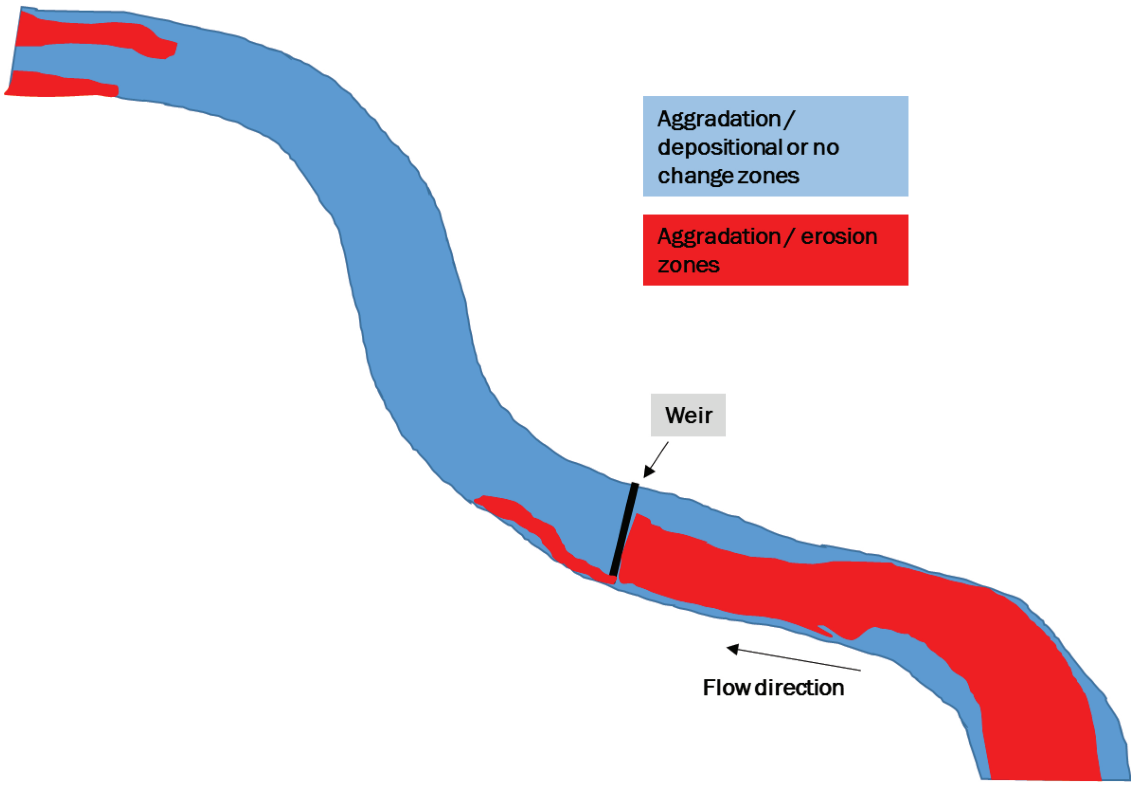

Figure 12.4 Potential bed elevation change following weir removal (from Im et al, 2011)

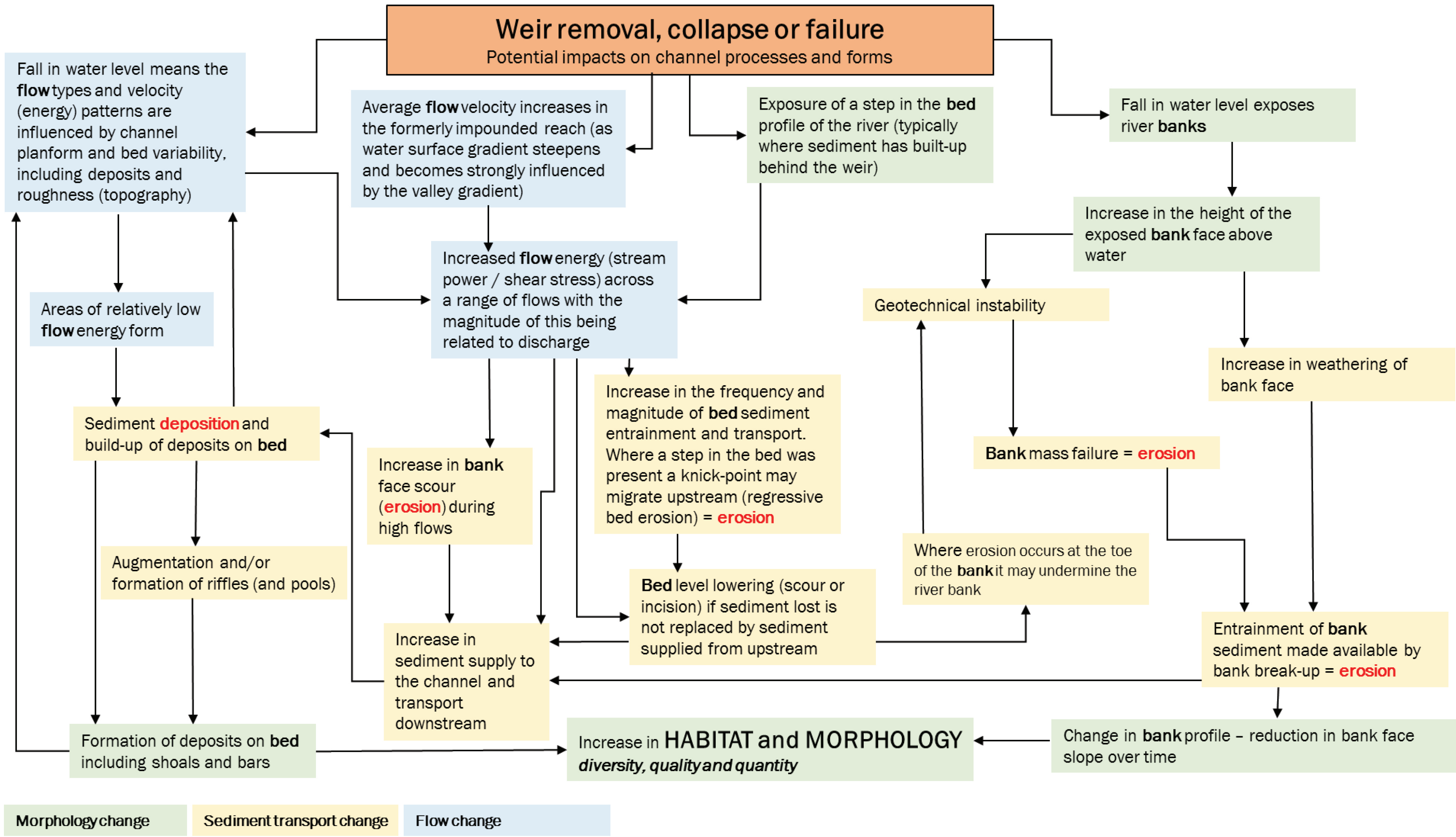

Figure 12.5 Potential impacts of weir removal or collapse on channel processes and forms (courtesy Duncan Wishart)

There are many potential measures to manage any negative responses to weir removal, including:

- Modification to channel morphology to manage the increase in hydraulic gradient upstream associated with removal of the weir structure. For example, riffle–pool sequencing, step-pools or rapids could be introduced to the river bed profile to dissipate the increase in energy gradient and reduce the risk of excess lateral or bed erosion. This morphology should be aligned to the river type and work with the natural processes at a reach and catchment scale.
- Modification to channel geometry through, for example, channel narrowing, widening, re-meandering or creation of a two-stage channel can help to dissipate increases in energy levels, possibly alongside morphological restoration as previously discussed.
- Soft bank protection at key points can be used to manage a risk of lateral bank erosion through such measures as coir rolls, pallets or willow spilling. These should be assessed as a suitable option first as they are more sensitive to natural river environments than traditional hard engineering solutions. In areas with particularly high water velocities following weir removal, hard engineering measures may be required to protect critical infrastructure.
- To prevent erosion of the channel bed following weir removal, in some cases, introduction of suitably-sized bed material may be required. This can be sized by an expert geomorphologist and through a hydraulic modelling and design process. Material used should ideally be aligned to natural sources and processes within the wider catchment. This could involve introduction of gravel, cobbles or boulders. Finer, cohesive sediments may also be used in some instances to provide cohesive river bed features.

Rock ramps are sometimes used to replace weir structures to maintain a head of water upstream, but to allow passage for fish upstream. These are normally composed of boulder, cobble and gravel material and should be designed as permanent features.

12.4.3 Weir modification or construction

Weir new-builds, ie the creation of an impoundment, disrupts the transport of sediment to downstream reaches. There is a risk of incision in downstream reaches because of sediment starvation, and deposition of fine sediment within the impoundment zone upstream.

Alternatives to weirs (**Section 5.3**) or weir removal (**Section 5.4**) should be considered in the first instance when formulating a weir scheme. Where new weir construction (**Section 5.5**) is required, geomorphological consideration should be given to the factors below. However, expert geomorphological assessment should be undertaken as potential impacts are often location specific.

- **Location** – locate weirs where there is less chance of the structure being outflanked (eg confined, steep valleys) and on steep sections of the river to reduce the impoundment length upstream. Weirs within bedrock reaches will minimise the impoundment length and geomorphological impact and provide a stable foundation for siting the weir. Locating a weir below a natural 'step' (eg bedrock layer), fall or cascade in the channel can reduce the impacts on sediment transport and conveyance, and consequently any response post-removal, decommissioning or failure of the weir.
- **Structure design** – incorporate a low flow notch to maintain some transport of sediment downstream and consider how this affects the sediment regime downstream. Orientation should ideally be at 90 degrees to the flow direction. Reduce the height of the structure above the river bed as far as is practically possible. Reduce the width of the channel it spans as far as is practical. Consider sloping the upstream face of the weir rather than a steep face to allow some transport of sediment across it. Reduce the requirements for significant bed and bank protection as part of the structure design by, for instance, locating a weir within a solid geology location where bed and bank stability is already high.
- **Channel modification** – minimise the impacts to existing channel geometry (width, depth and slope) as a result of installing the new weir. Reinstate any local damage to the river bed and banks as part of the construction process, including any associated diversion channel.
- **Weir maintenance, decommissioning and failure** – design should incorporate measures that reduce the risk of large volumes of sediment release downstream and that are unlikely to result in sediment mobilisation downstream during maintenance or decommissioning.

- **Related scheme structures** – consideration should also be given to not only the weir structure, but also the associated other scheme structures that may have an impact on geomorphological forms and processes. This could include structure wingwalls, pipes, outfalls, forebay tanks, hands off flow notches or orifices.

12.5 CONTAMINATED SEDIMENT

12.5.1 Overview

The removal, maintenance or modification of weir structures can under certain circumstances inadvertently increase the risk of mobilisation of contaminants that may be present within sediments deposited upstream of the weir. Therefore, without prior consideration and assessment, the possible presence of contaminated sediments in the river bed can lead to water quality impacts around and downstream of the weir structure. A similar type of risk also exists for works which extend through the channel bank into potentially contaminated ground though this is likely to be more of an issue in urban settings.

Contamination typically occurs as pollutants which are released into the river environment partition and accumulate in the finer and medium grained sediment fractions. Finer and medium grained river sediment fractions including clay minerals, rock forming minerals and organic matter are often characterised by having high specific surface areas and ion exchange capacities. This means that they can act as effective sinks for contaminants discharged into the river system. Typical contaminants which partition into river sediments include heavy metallic compounds (eg cadmium, copper, chromium, mercury, lead and zinc), persistent organic pollutants (POHs) such as polychlorinated biphenyls (PCBs), dioxins and polycyclic aromatic hydrocarbons (PAHs). While the original source of the contamination may no longer exist, contaminants can persist for many years in the sediment.

The risk of mobilisation of contaminants from accumulated sediments during works in or around weirs can be increased due to the potential for short-term sediment disturbance, or through direct exposure of contaminants to site operatives or members of the public. In addition, removal or alteration of a weir structure can alter the longer term movement and deposition of contaminated sediment further downstream of the original source.

Contaminants that have accumulated within sediments can affect chemical and ecological water quality for the following reasons:

- Sediments can remain potential long-term sources of contamination through partitioning of compounds into the water column, with an attendant impact on chemical water quality.
- During sediment disturbance there is the potential for increased mobilisation of contaminants.
- Contamination has a negative effect on sediment dwelling species, resulting in potential decreased biodiversity or complete disappearance of more susceptible organisms. Contamination levels can also be increased through the food chain.

While the presence of contaminated sediments can reasonably be anticipated in highly urbanised river reaches, contamination can also present an issue in other areas where the natural geochemistry contains elevated levels of certain contaminants (eg heavy metallic compounds in former metal mining areas) can also be of concern. The Hudson-Edwards *et al* (2008) has reported previously on this issue in relation to the extent of this problem in England and Wales, which includes an overview of metal concentrations in channel sediments in a number of UK river systems.

It should also be noted that other chemicals can be released to surface waters through industrial point discharge as well as diffuse discharge from urban and agricultural sources and they can continue to accumulate to potentially harmful levels in the river sediments.

12.5.2 Assessment

Development of an appropriate sampling strategy for the assessment of the risks posed by contaminated sediments requires a thorough desk and site-based investigation of contamination potential, which should be planned and implemented before carrying out in-channel works.

In the aquatic environment, the actual risk posed by contaminants present within sediments is determined largely by their respective mobility and bio-availability, which can be influenced

by a number of complex site specific conditions (eg pH, redox conditions, local surface water chemistry). Therefore, detailed assessment of contaminant impact can often be specific to the particular local circumstances requiring a combination of approaches. Typical approaches can include the following:

- Chemical analysis to determine total or leachable concentrations of selected hazardous contaminants, followed by direct comparison against pre-defined guideline values or statutory standards.
- Bio-assays to determine the toxic effects of contaminated sediments on selected aquatic species. In a number of European states (eg the Netherlands) bio-assays are used to assess the quality of dredged sediments (Den Besten *et al*, 2003).

Field inventory assessment is another approach involving the assessment of the taxonomic composition and abundance of benthic invertebrate fauna which are the most common biological water quality assessment indicators. However, this is a complex area as taxonomy can also be influenced by other factors such as habitat composition and nutrient availability.

Underpinning the sampling strategy is the requirement to develop a site or case specific conceptual site model (CSM), which is continuously refined and developed throughout the assessment process.

At a basic level the conceptual site model is aims to identify contaminant sources, potential receptor groups immediately surrounding and downstream of the weir and potential pathways linking the contaminants and the identified receptors. Within the conceptual site model, consideration must also be given to the potential for rapid changes in site conditions given the dynamic nature of river and sediment systems and the potential impact of the proposed in-channel works on these systems. In addition, the potential impact of the proposed in-channel works and how they might affect future sediment mobility should also be considered. In developing a sampling strategy for the sediments to provide adequate characterisation, typical factors which are considered can include:

- The potential volume of the sediment upstream of the weir that might be disturbed and their physical characteristics.
- The sensitivity of the surrounding environment, particularly downstream of the site.
- The history of the area surrounding the weir (including the immediate surrounds and upstream areas), including the results of any previous sampling, or knowledge of known discharge(s) or potential sources of contamination in the surrounding area.
- Potential short-term effects on water quality and in some cases long-term effects if, for example, alteration of a weir structure is likely to alter the future sediment deposition characteristics in the downstream river channel.
- The proposed approach to dealing with the accumulated sediments (eg retention in channel, retention/reuse on surrounding land, off-site disposal to landfill).
- Likely disposal methodologies, routes and available sites for cases where sediments are to be removed from the channel. In this case, an appropriate analysis suite must also be designed to match the information required for the preferred disposal route and the results must be assessed against guidance.

In relation to sediment accumulation behind weirs, there is little in the way of specific guidance or case study information in the literature. However, a typical assessment approach in order to develop a management strategy to mitigate adverse impacts could involve conducting staged investigations. For example, the initial (preliminary) stage could involve sampling and analysis of accumulated sediments to determine total concentration levels to assess whether the levels are high enough to warrant concern (eg by assuming all contaminant is likely to mobilise into water and/or is bio-available). If this initial assessment indicates there may be an issue then a second investigation stage is appropriate, focussing on contaminant bio-availability and other lines of evidence to determine whether there is the potential for impact.

In relation to the setting of assessment criteria to evaluate the impact of contaminated sediments on water quality, UK guidance is limited. For example, Hudson-Edwards *et al* (2008) have previously sought to develop draft interim sediment quality guidelines, in relation to their obligations under the Habitats Directive to protect and improve ecological health at Natura 2000 sites. The guidelines are based upon the Environment Canada threshold effect level (TEL) and predicted effect level (PEL) approach (CCME, 2001). A TEL represents a concentration below which sediment-derived contaminants are not thought to represent a significant hazard to aquatic organisms, while

Box 12.3 ***Dealing with contaminated sediment***

Refurbishment was planned for a weir in an area with a long and varied industrial history. There was concern that contaminated sediment in the river bed would create health hazards during the work, affect the reuse or disposal of materials, or affect the design of materials for durability.

A desk study was carried out to identify historic land uses and likely contaminants, and to inform sampling and testing. As a result, the site was classed as amber (medium risk) and arising's from site investigation had to be contained and disposed of off-site, rather than returned to the river. Soil and water samples were taken from the bed and boreholes upstream and downstream of the weir, and tested for metals and organic contaminants. Chemical tests for nutrients were omitted as the spreading of material on land for agricultural or ecological benefit was unlikely to be unviable.

Most contaminants were below soil guideline values or the limit of detection, although some samples contained high levels of phytoxic elements (which are toxic to plants). This meant that although excavated material was unlikely to pose a hazard to health, it would be unsuitable for reuse in places where plants were grown.

As a result, the works were required to avoid disturbing in-channel sediments as far as possible and avoid reusing potentially contaminated excavated material. Contamination testing and classification of surplus sediments was required, with off-site disposal of arising's at an appropriately licenced facility. Sulphate resistant concrete was also specified for construction purposes.

Site investigation data were issued within tender documentation in order to make contractors aware of potential contamination-related issues that would need to be considered during construction works at the site.

the PEL represents the lower limit of the range of concentrations associated with adverse biological effects. The limitations of this approach arise from site-specific circumstances that affect both the bioavailability and toxicity of particular types of contaminants, and which are linked to a number of physical and chemical properties of the sediments such as pH, particle size, organic matter content etc. However, use of such values can serve as a useful trigger for further investigations and assessment on a site specific basis.

For situations where contaminated materials may be retained and there is increased risk of exposure to human receptors, there is a large volume of published information on the assessment of the risks arising directly from land contamination (eg Defra, 2012). Coupled with this has been the development of soil guideline values (SGVs), an example of generic assessment criteria which are typically used in the preliminary evaluation of the risk to human health from long-term exposure to chemicals in soil materials (Defra and Environment Agency, 2014). They are therefore are not appropriate for addressing the short term risks through potential exposure to contamination.

To allow safe (and where materials are used to confer benefit onto surrounding land, sustainable) disposal of sediments sampling and analysis should be carried out prior to in-channel works in order to characterise the sediments. The Canal & River Trust sediment screening suite provides a basic screen for analysis of contaminants, which includes a range of potential metallic, inorganic and organic contaminant types (AINA, 2013). Similar screening suites have also been derived to characterise dredged sediments for dewatering and land spreading purposes, which also typically include assessment of nutrient levels when materials are deposited onto agricultural materials to confer benefit (Broads Authority, 2009).

Should it be necessary to remove excavated or dredged sediments off site, for example through disposal at an appropriately permitted landfill or exempt facility, Waste Acceptance Criteria (WAC) testing will normally be required in order to classify the waste materials.

12.5.3 Management options

Following completion of a contamination risk assessment, options for management sediment can be formulated in order to mitigate adverse impacts. Typical options for dealing with sediments can include a combination of some, or all, of the following measures:

- Retention on site where risk assessment demonstrates that contamination levels are acceptable and are unlikely to lead to a reduction in overall river quality (both from a chemical and ecological perspective), or have an adverse effect on the surrounding environment. This option is attractive because as it reduces the need to find alternative disposal routes.
- Treatment to allow for beneficial reuse (eg for as a construction material), or to reduce disposal volumes. Such treatment might include, for example, immobilising contaminants, or improvement of the handling characteristics of the material (eg reduction of moisture content).
- Excavation and disposal of arisings where contamination levels would lead to unacceptable levels of impact.

Where contamination levels are significant, excavation and disposal is likely to be the option chosen during weir rehabilitation. This would also equally apply if the presence of invasive plant species (eg New Zealand Pigmyweed, *Crassula helmsii*) is known, or suspected in sediments removed during weir rehabilitation works. The advantages of this approach is that a clean-up level can be achieved through contamination source removal and uncertainty regarding future environmental impact is reduced. The principal limitations are that it is usually more complex and costly than *in situ* management, and that the level of uncertainty associated with estimating residual impacts can be significant.

Other management options could include capping of contaminated sediment with a subaqueous covering or a cap of clean material. Depending on the contaminants and sediment conditions present a cap is generally designed to reduce risk through the following primary functions:

- Physical isolation of the contaminated sediment sufficient to reduce exposure due to direct contact and to reduce the ability of burrowing organisms to move contaminants to the cap surface.
- Stabilisation of contaminated sediment and erosion protection of sediment and cap sufficient to reduce re-suspension and transport of contaminants into the water column.
- Chemical isolation of contaminated sediment sufficient to reduce exposure from dissolved contaminants that may be transported into the water column. The cap might typically comprise clean sediment, geotextiles, liners etc.

Monitored Natural Attenuation (MNA) is another potential approach for long-term management of retained sediments. It is based on reliance of naturally occurring processes to contain, eliminate, or otherwise reduce the bio-availability or toxicity of contaminants in sediments. This approach would normally be supported by monitoring for a range of water quality indicators (which could include ecological parameters) to evaluate whether an agreed acceptable level of risk is maintained, or diminished with time.

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13 Hydrology and hydraulics

13.1 INTRODUCTION

This chapter gives a broad general overview of hydrological and hydraulic design processes for weir structures. For more detailed guidance the reader should see specialist hydrology and hydraulics textbooks that cover weir design (eg Novak *et al*, 2007).

As previously noted all design should be carried out with the avoidance of risk in mind and following a hierarchy of risk control. In the UK, the designer must comply with duties set out in CDM 2015 and follow the measures set out in the guidance that accompanies the Regulations.

The principal function of a weir, to safely manage upstream water levels over a range of flows, depends almost entirely upon its hydraulic geometry. A good hydrological understanding of the river is required to estimate the likely range of flows that a weir will be required to pass. The level, shape, size and configuration of the weir structure must then be designed so that the hydraulic performance of the weir meets the functional objectives of the project. Hydraulic design must also reduce, to an acceptable level, the risk posed by hydraulic conditions to the weir structure, surrounding infrastructure and to river users and the public. Depending on the project, hydraulic design will include:

- hydrology, flow conditions and design floods (**Section 13.2**)
- selecting a preliminary hydraulic geometry (**Section 13.3**)
- other hydraulic features (**Section 13.4**)
- hydraulic modelling (**Section 13.5**)
- energy dissipation (**Section 13.6**)
- scour and scour protection (**Section 13.7**)
- hydraulic design for specific functions (**Section 13.8**).

13.2 HYDROLOGY, FLOW CONDITIONS AND DESIGN FLOODS

13.2.1 Hydrology and flow range

The range of flows likely to be experienced at any weir site will vary with the size and location of the river and the nature of the catchment upstream. However, significant seasonal variation can be expected and a weir should be designed to operate satisfactorily in all flow and water level conditions. **Section 13.2.3** provides further discussion of design cases. It is important that all available flow data for a river are obtained when planning the construction, rehabilitation or demolition of a weir. As can be seen in **Figure 13.1**, hydraulic conditions at a weir can vary dramatically as flows change.

Showing the weir when the bypass is not operating

Showing the weir when the river is in flood.

Figure 13.1 Weir on the River Exe flood bypass channel

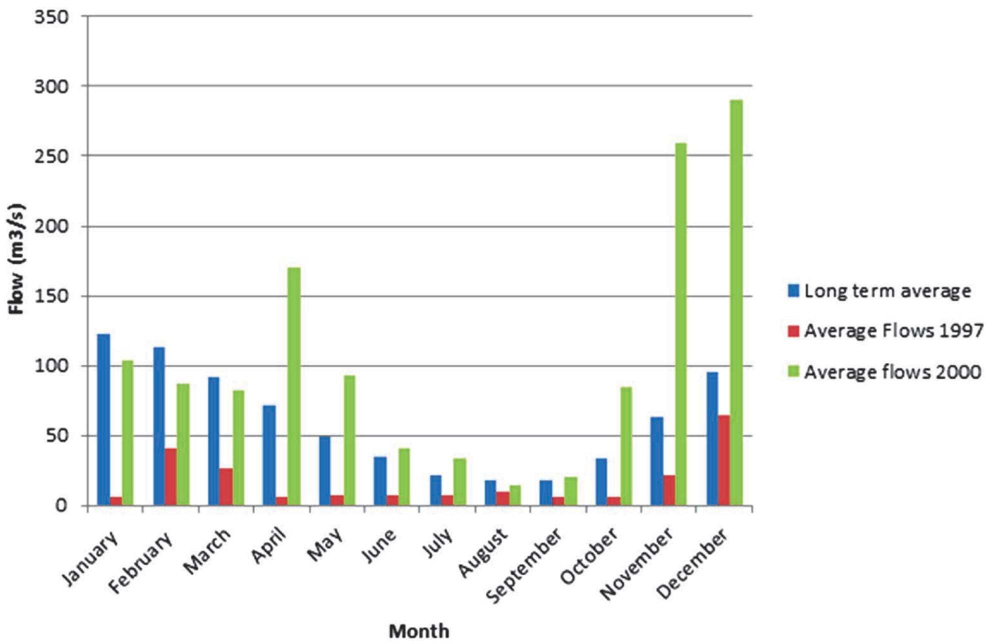


Figure 13.1 Flows in the River Thames at Kingston

Rivers in the UK generally exhibit significant seasonal variation in flow, with higher flows in the winter months between October and April.

Figure 13.2 is based on data for the period 1970 to 2013 (43 years of record). It can be seen that the long-term average monthly flow shows a distinct seasonal pattern, with the highest flows generally occurring in January, and the lowest in July, August and September. However, examination of actual monthly average flows for the years 1997 and 2000, which were unusually dry and unusually wet years, respectively, shows that the average flow rates hide a wide range of variation. For example, the long-term average flow for the month of October is about 34 m^3/s, but in 2000 the monthly average was more than double this at 85 m^3/s and in 1997 only 5 m^3/s. It is important to acknowledge this natural variation, not only in terms of the design of a weir, but also in terms of planning construction activities in the river.

Also, as the peak flow experienced in 2000 exceeded 300 m3/s on at least one day in each of three months of October, November and December, with a recorded maximum of 440 m^3/s. The highest recorded peak occurred in November 1974 when the discharge reached 531 m^3/s. At the other end of the scale, typical low flows in the summer months are about 20 m^3/s, but fell to around 7 m^3/s for the summer months of 1997. In late August of 1976, the UK's famous drought year, flow all but ceased.

There are numerous methods that have been used for calculation of floods historically, including the use of maximum observed floods, flood frequency analysis and rainfall runoff techniques. The Centre for Ecology and Hydrology (CEH, 1999), formerly the Institute of Hydrology, describes rainfall runoff methods, rainfall frequency estimation and statistical procedures for flood frequency estimation, but emphasises the use of gauged flow records and the transfer of data from gauged catchments to ungauged catchments. Flow series for gauged catchments in the UK can be obtained from the National River Flow Archive (NRFA) held by the CEH.

Other considerations relating to flow conditions include:

- What will the visual appearance of the flow be in low periods?
- Will some flow conditions restrict the passage of migrating fish?
- At what flows might dangerous hydraulic conditions occur?
- Will the weir form a tempting crossing point at low-flow conditions, and will this be safe?

13.2.2 Flow conditions

In simple terms, the hydraulic impact of a weir increases the upstream water level. The water level upstream of the weir is dictated by the head (**Figure 7.1**) required to drive the flow over the weir. It should be noted that the impact of the weir on the upstream water level is not confined to the immediate vicinity of the weir – there is 'backwater effect' (see **Figure 13.3**), which extends some way upstream of the weir.

The increase in water level will, for the same flow rate, reduce the average velocity in the upstream reach. This will have an effect on the sediment transporting capacity of the channel. The lower velocities will have knock-on effects in terms of water quality and habitat type. There are downstream issues as well, namely that there is likely to be a localised increase in turbulence and flow velocity immediately downstream of the weir. This has the potential to cause erosion of the river bed and banks, and may result in the creation of a deep pool downstream of the weir, and deposition in the form of a shoal further downstream.

As the flow over the weir changes, the head (depth of water) over the crest will also change. This results in there being a relationship between the discharge over the weir and the upstream head above the weir crest. It is this principle that allows weirs to be used for discharge measurement. This mathematical link between upstream head and flow remains valid while the downstream water level is low enough to have no effect on upstream water level, ie while the flow remains 'modular' or free flowing. As flow increases in the river, the downstream water level will naturally increase because the river is carrying extra water.

In general, modular flow across a weir is described by the weir equation:

$$Q = C.Bz.h^{3/2} \tag{13.1}$$

Q = flow (m^3/s)

C = discharge coefficient dependent on weir crest shape

B = weir crest length (m)

h = head over weir crest (m)

In order to achieve the required discharge characteristics, the crest length of the weir can be increased or decreased within the available space in the river, the crest level can be lowered or raised to increase the head driving flow over the crest, or the crest shape can be altered to increase the efficiency of discharge.

Eventually the water level will increase to a point where water no longer freely discharges over the weir crest, and a situation occurs where a change in downstream water level affects the upstream level. When this occurs the weir is described as being 'drowned', 'submerged' or operating under 'non-modular' conditions (see **Figure 13.3**). Instead of flow being a function of upstream head only, it is now dependent upon both upstream and downstream levels.

Once a flow gauging weir starts to become drowned it is unable to provide accurate flow measurement, unless specific arrangements have been made to measure downstream water levels as well as upstream. As downstream water levels continue to increase still further, above the minimum levels that caused drowning, then the impact that the weir has on upstream water levels becomes less significant (see **Figure 13.3**).

13.2.3 Design floods

It is a common misconception that the hydraulic capacity of a weir should be selected for a prescribed return period flood, as might be the case for a dam spillway. Weirs differ from dams in that, by definition, they do not impound significant volumes of water at a level above the surrounding topography. For flows larger than the bank full flow a weir is likely to be drowned in the river channel with flow circumnavigating the structure in the floodplain. This is not an abnormal condition, as would be the case for overtopping of a dam. After flows have risen above the bank edge and into the floodplain, the weir typically plays a lesser role in influencing water levels.

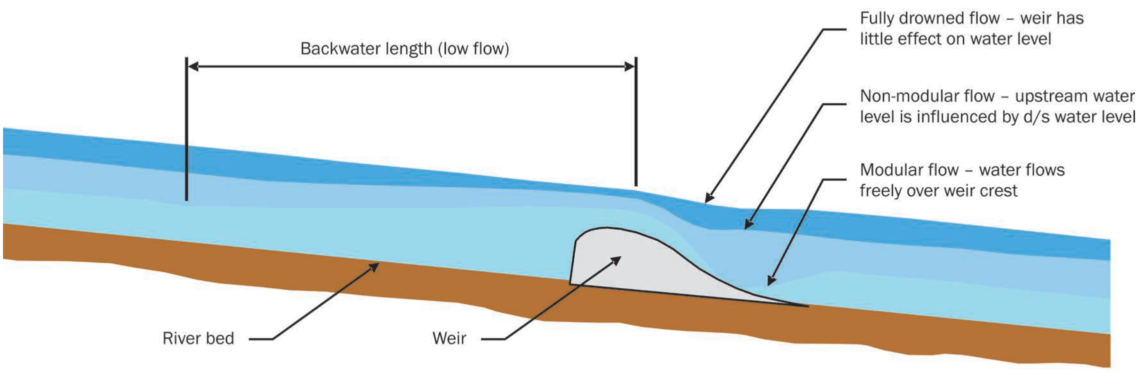


Figure 13.3 Modular, non-modular and drowned flow conditions

Selecting a design hydraulic capacity for a weir is a site-specific exercise, but is usually a matter of considering the acceptable afflux with respect to the topography of the upstream river banks and the value of the flood and drainage receptors present, ie the weir capacity is sized to prevent out-of-bank flow for a given return period flood and to avoid impeding drainage to areas upstream. If the upstream river bank has been designed to contain a 100-year return period flood, it may be appropriate to design the weir capacity to match this. However, it is a considered choice to manage flood risk and acceptable afflux upstream of the weir, and is not an absolute design criteria related to the hazard of breach, as is the case with a dam.

Where a new weir replaces an existing weir, it has been common practice in the past to match the flow capacity of the new and old weirs at bankfull level. In this way there is no increase in the frequency of out-of-bank flow. The capacity of other structures in the reaches upstream and downstream of the weir should also be examined as in some cases the weir is not the restriction on flow when the river banks are full. Capacity provided in excess of upstream or downstream constrictions (such as bridges) can be expensive and may have no influence on the frequency of out-of-bank flooding. **Figure 13.4** illustrates some of these considerations.

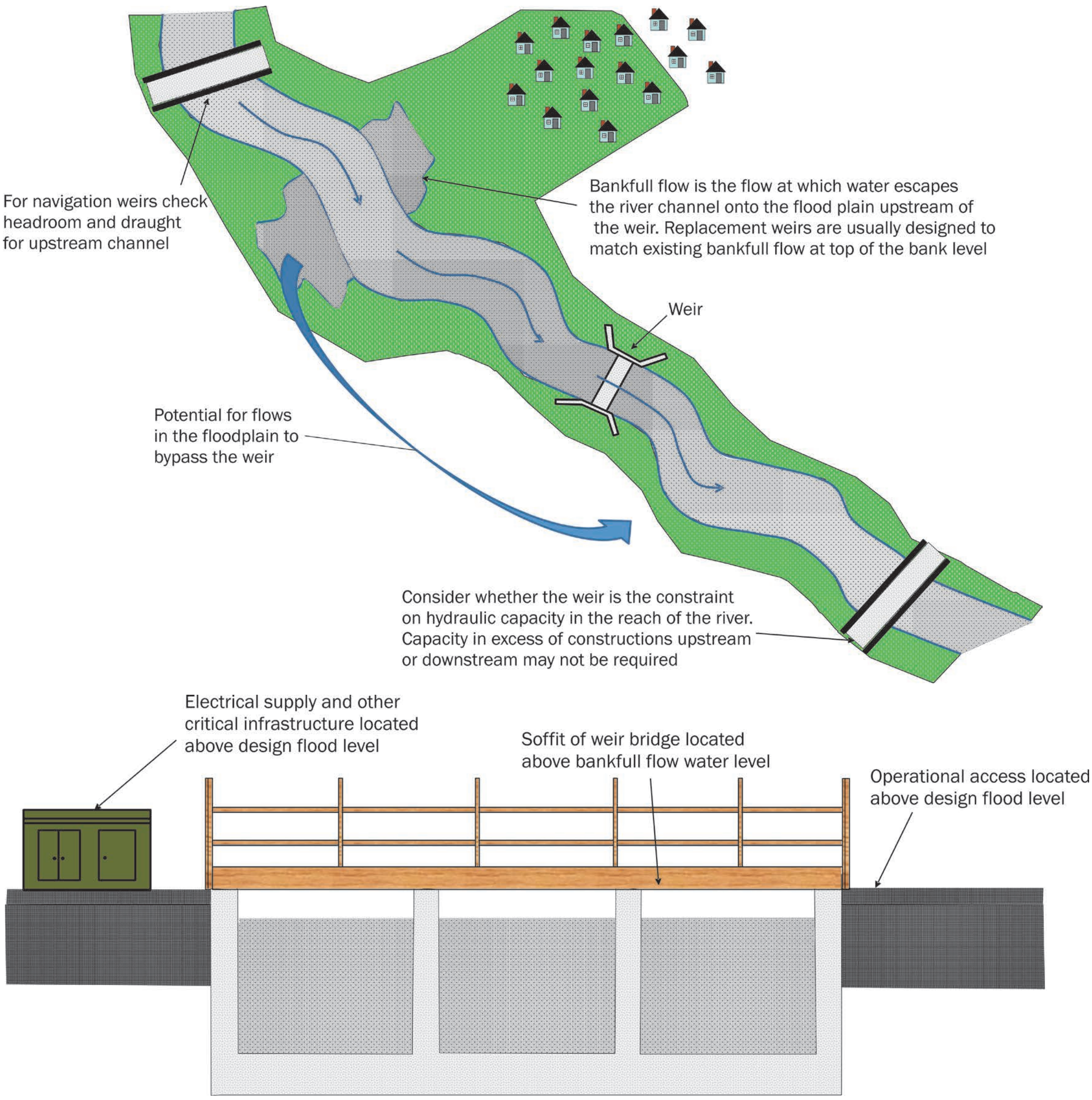


Figure 13.4 ***Considerations during review of design floods and capacity***

13.3 SELECTING A PRELIMINARY HYDRAULIC GEOMETRY

13.3.1 General approach

The desired range of upstream water levels under normal flow conditions will be well defined by the functional requirements of a weir and constraints on changes to upstream land drainage or groundwater conditions. Constraints under normal flow conditions may include keeping water levels below the elevation of outfalls and upstream land drainage. For example:

- A weir intended to regulate water levels for river navigation might need to retain water at a certain level to prevent boats from grounding, and to limit flood rise for flows of a certain level to prevent boats leaving the river channel or hitting bridges crossing the river.
- Conditions over a gauging weir will usually need to remain modular for a given range of flows.
- A diversion weir for a hydropower scheme may need to avoid impact upon the tailrace of an upstream scheme.

The weir crest level (or top of gate level) can be defined based on the site-specific constraints and weir requirements. For gated weirs, gate crest levels are usually set marginally above the normal operating level so that the pond level can be raised marginally during low flows and in some cases to prevent wave lap and ice formation on the gates.

After consideration of flood risk to surrounding receptors, a design flow with a given return period and an acceptable afflux for this flow will have been selected as described in **Section 13.2**. Once these criteria are established, initial sizing of the weir can take place. This is usually a case of selecting crest length or gate number/geometry to pass the design flow with acceptable afflux.

The width of the weir should usually broadly match the regime width of the upstream waterway. If the river channel is well established or heavily engineered, the required width of the weir should be clear. For rivers where there is no regular channel, the regime width of the upstream channel should be calculated (see Novak *et al*, 2007). In these cases, river training works may be required to ensure a good approach to the weir. Guidance for design of river training works can be found in Kirby *et al* (2015).

For gated weirs, care should be taken to allow for piers of sufficient width to accommodate embedded parts and holding-down arrangements. In calculating hydraulic capacity, allowance should be made for the pier widths and hydraulic contraction at the piers, velocity head of the approaching flow, and whether flow is affected by submergence of the weir by downstream water levels. For more detailed guidance see Novak *et al* (2007).

It is important to pay particular attention to the performance of a weir in flood conditions, when water is likely to flow on the adjacent floodplain. In such conditions there is a risk of the weir being bypassed, and this could adversely affect the weir structure if it has not been allowed for in the design. In particular, the bypassing flow could undermine the weir wing walls or abutments, ultimately leading to the formation of a new channel leaving the weir stranded. This problem is much less likely if the weir has only a modest effect on the water level in the channel in flood conditions.

In cases where the weir is likely to be bypassed, it may be appropriate to design for this. A channel can be constructed around the weir, to direct flood flows at a safe distance around the structure. For perched rivers that flow within flood banks above the wider floodplain, a formal fuse bund that is deliberately breached during major flooding can be constructed in order to direct flooding and prevent an uncontrolled breach. More typically in the UK, a natural depression in the upstream bank will be the point at which the river spills out-of-bank and flows will bypass the weir over the wider floodplain. As the floods recede, flows tend to drain back into the river channel at another low point in the banks. Care should be taken to ensure that this occurs at a sufficient distance from the weir to reduce the risk of scour damage to the structure.

Section 5.2 describes the common weir shapes in plan and cross-section. The following sub-sections summarise the hydraulics for common weir shapes and their particular applications.

13.3.2 Broad-crested weirs

Most weirs in rivers can be approximated to broad-crested weirs although their structure and form can vary significantly. Broad-crested weirs comprise an overflow structure with a horizontal crest in the direction of flow. The weir generates a localised increase in water velocity and a reduction in water level across the crest. Broad-crested weir structures can have control sections of a variety of shapes including triangular, parabolic, trapezoidal and circular.

Determination of the hydraulics at broad-crested weirs is detailed in standard hydraulics textbooks such as Novak *et al* (2007). These references provide a sufficient level of detail and accuracy of the stage-discharge relationship for modular flow situations. Alternatively reference can be made to Bos (1989) or other references on discharge measurement, whether or not the function of the weir is for flow gauging.

13.3.3 Sharp-crested weirs

A sharp-crested weir (or thin plate weir) is an overflow structure where the length of crest in the direction of flow is extremely short, typically of the order of two millimetres or less. For these structures, the crest length of the weir is short enough not to influence the head-discharge relationship and the occurrence of critical flow is not relevant for discharge calculation. The behaviour of the sharp-crested weir is analogous to orifice flow with a free upstream water surface (Bos, 1989). ISO 1438:2008 and Bos (1989) present formulae for flow calculation at sharp-crested weirs including the derivation of coefficients required for discharge calculations.

Sharp-crested weirs are typically used in laboratories, small streams and in sediment-free water (ISO 8368:1999), where highly accurate discharge measurements are required. As with broad-crested weirs, the control section of sharp-crested weirs can be rectangular, triangular, circular, trapezoidal shapes or other more complex forms.

In practical terms, the designer is more likely to encounter sharp-crested weirs when examining flow over the top of hydraulic gates during flood conditions, or where the gates have a dipping function so that they can be lowered to pass 'cresting' flow.

13.3.4 Ogee weirs

The shape of the weir crest for ogee weirs is curved to match the profile of the water surface under the nappe of water flowing over the structure. This is generally recognised as being the ideal weir profile shape for the conveyance of flood water (high discharge for a given upstream head) and is commonly used in dam spillway design although dams are outside the scope of this guidance.

Although the shape of the nappe will vary with upstream water head, standard design principles can be used to determine the optimum weir crest shape, thereby reducing the risk of structural damage from variations in pressure between the upper and lower surfaces of the nappe. These relate to the conveyance capacity required across the weir, the range of upstream water levels expected during flood conditions and the dimensions of the upstream and downstream sides of the structure. Details of the design principles for ogee weirs are summarised in USDotI (1987).

13.3.5 Compound weirs

Weir structures may comprise one or more weirs across a watercourse, acting in parallel to control upstream water levels and convey flow downstream, Detailed guidance on the design and assessment of structures comprising multiple weirs that may be of different types is contained in ISO 14139:2000.

13.3.6 Labyrinth weirs

A labyrinth weir is a linear weir that is corrugated in a plan-view to increase the crest length for a given channel or spillway width. Due to the increase in crest length, a labyrinth weir provides an increase in discharge capacity for a given upstream driving head, relative to traditional linear weir structure (Tullis and Crookston, 2011). This effect is most pronounced during low flows, but diminishes as flows increase and the weir starts to become drowned. A significant portion of the published information regarding the design of labyrinth weirs has been compiled by Falvey (2003).

13.3.7 Side weirs

Side weirs are used widely in order to divert flows from rivers, canals, sewers and reservoirs. However, the hydraulic behaviour of this type of weir is complex and difficult to predict accurately

by simple methods. May *et al* (2003) present a procedure that was developed by analysing published data on the performance of side weirs and using the results to calibrate a predictive numerical model. Presented in the form of graphs and simplified equations, the method enables the flow rate discharged by a side weir to be determined by direct calculation.

13.4 OTHER HYDRAULIC FEATURES

13.4.1 Appurtenant features

Appurtenant features such as fish passes take up space in the channel and can be located in the bank if hydraulic capacity constraints dictate. Care should be taken to ensure that the selected weir geometry allows biological hydraulic requirements to be met, including attraction flow, drop height, velocity and turbulent energy limits and sufficient depth of water for passage. Further guidance can be found in **Section 11.5**.

Where sediment management is a consideration, the hydraulic arrangement should be designed to manage sediment transport in the vicinity of the weir, as might be required for geomorphological/environmental reasons, to manage the quality of abstracted water, or to prevent occlusion of an abstraction point. For example, scour sluices may be include within a weir structure to allow periodic scouring of sediment upstream of the weir.

Other geometries that are dependent upon flood levels, such as walkway levels and gate lifting arrangements, can be tentatively laid out during the initial stages of design (see **Figure 13.4**). In doing so, the following principles should be considered:

- The soffit level of bridges and access walkways over weirs should be set at a suitable height to allow floating debris pass freely under the structure. A minimum of 600 mm clearance above the design flood level is typical.
- The bridge should remain clear of flood waters so as not to pose obstruction to flow when the river is within its banks. For flood risk reasons, some responsible authorities may specify that bridges should be above a higher return period flood level. This is not usually necessary as once the river flows out-of-bank, the obstruction caused by a weir bridge is in most cases negligible when compared to the capacity of the wider floodplain. Walkways and approaches designed to be clear of high return period floods may appear very high during normal flow conditions.
- For gated weirs, the bridge should remain clear of flood waters so that operatives can continue to work the weir until the gates are all open. Access routes to the weir bridge should also be raised for this reason.
- Electrical junction boxes and lighting should be located above the design flood level.

13.4.2 Hydraulically-induced vibration

With a very short weir crest length in the direction of flow, as is the case for flow over a hydraulic gate, the nappe (the sheet of water flowing over the crest) is likely to be disconnected from the downstream face of the gate and an air pocket will form under the nappe. A sufficient supply of air should be maintained to this air pocket to prevent inconsistencies in the flow patterns across the structure and, in exceptional circumstances, resonance that may cause structural problems (Bos, 1989). Ventilation can be achieved using vents in the weir piers, gate wings to separate the edges of the nappe from the gate piers and allow side entrance of air, or flow splitters along the top of the gate to break up the nappe and allow air to enter underneath. Where gates are relatively small and can be ventilated from the side only, wings are usually preferred to flow splitters as the latter have a tendency to collect trash.

Flow separation and reattachment underneath a gate can cause similar problems and should be avoided by the selection of suitable sill details to discourage reattachment of the flow stream once it has separated from the gate. It is also good practice to design gates so that the hydraulic forces on the gate as it approaches closure, act in a manner to assist closure. This helps to prevent vibration of the gate as it nears a closed position.

Further guidance on hydraulically-induced gate vibration is given in specialist hydraulic gate design texts (Lewin, 2001 and Erbisti, 2003) and in papers such as Noble and Lewin (2000).

13.5 HYDRAULIC MODELLING

Once a preliminary hydraulic geometry has been selected, hydraulic modelling of the structure may be necessary in order to refine the design and to check that the performance of the weir is acceptable, in particular to confirm discharge characteristics and to demonstrate that changes in water level and flood risk are acceptable over a range of flows.

Hydraulic modelling of weir structures can be done in the following ways:

- Desktop design – use of basic fluid dynamics and empirical relationships developed in laboratory conditions that are applied to various sites.
- Physical modelling –setting up a scale model of the site to produce direct simulation of the hydraulic phenomena.
- Numerical modelling including computational fluid dynamics (CFD) – the use of numerical methods and algorithms to solve problems that involve fluid flows.

Desktop design

Desktop design uses the principles of basic fluid dynamics along with empirical design from relationships developed in a laboratory to determine basic hydraulic characteristics and conditions at a site. This method is useful for simple hydraulic arrangements and for obtaining a preliminary understanding of hydraulic conditions, which can be later verified by a physical model or a numerical model.

Desktop design should always be carried out as the first step in developing the preliminary hydraulic geometry, even if modelling is to be carried out, in order to gain a good initial understanding of flow conditions and to determine what flow conditions and geometries should be modelled.

Indicators of the need for a physical or numerical model include:

- a weir geometry that is complex (ie the weir cannot readily be represented by a single cross section)
- a weir shape/form that varies from standard structures
- where specific hydraulic features are required (or need to be avoided) in certain flow conditions (such as might be required for the safety of canoeists)
- where an existing structure is being significantly modified to achieve specific hydraulic performance.

The main advantage that a model study offers over desktop design is the ability to test a range of solutions over a wide range of flow conditions.

Physical modelling

Physical models have been used for hydraulic modelling since the mid-19th century. They are used as they allow the direct simulation of hydraulic phenomena, which is useful in complex situations where the physics of a site may not be covered by mathematical models. They can give an indication of likely morphological behaviour and sediment transport, which in many cases cannot be accurately modelled numerically. A potential issue with physical modelling is the impact of scale effects. Scale effects are the error resulting from modelling the situation based on scales chosen to suit the dominant action (inertia, gravity etc) and consequently other forces are distorted. Scale effects can sometimes be overcome by using natural scale models, however in some situations (particularly when modelling the transport of fine sediment) scale effects can be a significant barrier to accurate results.

Another challenge presented by physical modelling is that the model extent and flow is limited by the constraints of the basin available. Retention of the physical model over a long period of time is not usually possible, which limits the possibility of future use if there is a need to re-examine the model. Physical models are less flexible than numerical models as, while small changes in design are relatively easy to implement, some changes may require the whole model to be rebuilt.

Physical models can also be useful to show the public and other non-technical parties what is being proposed.

Numerical modelling

Numerical hydraulic models have been in use since the 1940s. Since then, numerical models have become increasingly accurate and computing resources for processing have increased exponentially, allowing faster model

runs and modelling of more complex hydraulics. The advantages of numerical modelling include the following:

- relatively cheap to set up than physical models (the majority of costs relate to purchase of the software and specialist hardware to handle the high processing requirements).
- easily adjusted to reflect changes in design
- provide multiple tools for detailed analysis and simplify measuring and communication of output
- they do not suffer from scale effects, as opposed to physical models that do
- they can model large areas and flows
- easier to store than physical models and can last for a longer time (assuming the software used to generate the numerical model is still in use in the future).

However, numerical models are far from being the standalone modelling method as models may still need to be validated with physical models and inputs are based on a series of assumptions that are subject to the skill of the modeller. In some cases, a physical model may be the only way to obtain an accurate representation. In addition it should be noted that where representation of a mobile bed is required numerical modelling currently uses some empirical relationships rather than a full physical-based representation.

Differences between 1D, 2D and 3D models

Flow over a weir, in reality, occurs in three dimensions, however, it is often appropriate to simplify matters and examine a problem in one or two dimensions by making assumptions about flow behaviour in the neglected dimension(s). It is important to understand what these simplifications are and when it is acceptable to use a simplified analysis (see **Table 13.1**).

For river weirs, 1D models may be appropriate for simple geometries that are relatively consistent across the channel width. Modifications to standard hydraulic formulae can be made to allow for interference in the flow pattern caused by structures such as wingwalls and piers and an approximation to variation in channel conditions in the lateral direction can be made by modelling different parts of the channel and structure separately.

2D models require additional resources and information to construct. They can be useful to understand situations where flow in the lateral direction is important, but flow in the vertical direction is less so. They are typically used for wide weir structures, complex approach channels, weirs near to channel bends, with multiple gates or those orientated obliquely to the channel, or side weirs that offtake perpendicularly to the main direction of flow. They may be used where a more detailed understanding of velocities is required. Where vertical variation of velocity is important, for example in the design of scour protection, sediment management, or to predict geomorphological change, vertical velocity profiles can be derived using flow continuity.

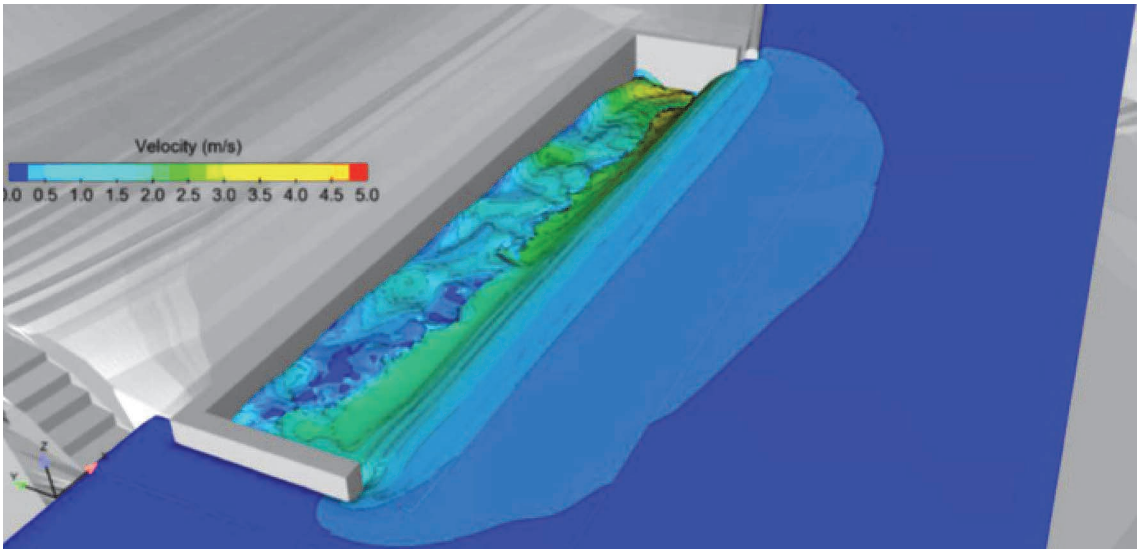
Three-dimensional models require even greater resources and input information. They are typically used for more complex hydraulic situations where flow behaviour in all three dimensions is important. This might be the case for non-standard weir geometries, flow approaches, stilling arrangements and intakes or where particular hydraulic performance is critical.

Table 13.1 ***Differences between 1D, 2D and 3D models (after CFSCM, 2008)***

Property	1D modelling	2D modelling	3D modelling
Flow direction	Prescribed (streamwise)	Computed (but horizontal)	Computed
Transverse velocity	Neglected	Computed	Computed
Vertical velocity	Neglected	Neglected	Computed
Velocity averaged over:	Cross sectional area	Depth at a point	Element
Transverse velocity distribution	Assumed proportional to conveyance	Computed	Computed
Transverse variation in water surface	Neglected	Computed	Computed
Vertical variations	Neglected	Neglected	Computed
Unsteady flow routing	Can be included	Can be included	Can be included

(a) Physical modelling of Guddu Barrage, Sindh Province, Pakistan

(b) Physical modelling of Kabeli 'A' Barrage, Kathmandu, Nepal



(c) Computational fluid dynamic model of a tumble bay weir

Figure 13.5 Examples of hydraulic modelling

13.6 ENERGY DISSIPATION

At a weir, the potential energy held in the elevated water impounded by the weir is converted into kinetic energy as water flows over the structure. The resulting fast-moving flow has the potential to cause damage to the weir structure and the downstream channel.

The Froude number (Fr) is a dimensionless value that describes different flow regimes of open channel flow. The Fr is a ratio of inertial and gravitational forces. Flow is said to be subcritical for Frs of less than unity and supercritical for Frs of greater than unity. In general deep, slower moving tranquil flow is subcritical, and shallow, faster moving rapid flow is supercritical.

It is usual to design a stilling basin as part of the weir structure, so that supercritical flow conditions over the weir glacis transition (in a hydraulic jump) to subcritical conditions that are compatible with the downstream river conditions. A proportion of the energy released during this transition is dissipated on the hard weir structure, and is not conveyed further downstream where it may cause damage to soft banks or undermining of the weir structure.

These simple basins rely on the momentum of shallow fast moving flow entering the basin being arrested by impact with a body of deeper almost stationary water. The resulting turbulence allows energy to be dissipated safely within the basin.

In certain situations, savings in construction cost can be made using other types of stilling basins. The material prepared by the United States

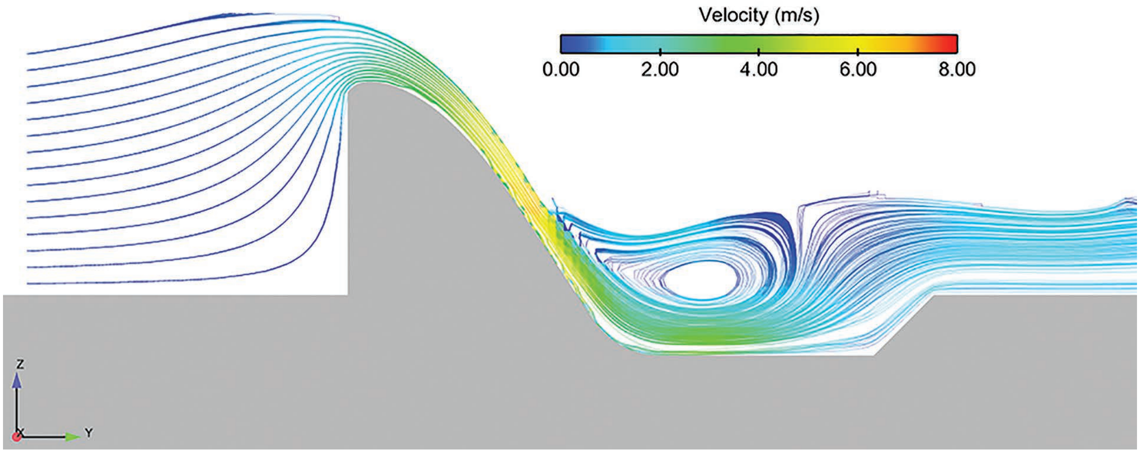


Figure 13.6 CFD model of a stilling basin

Bureau of Reclamation (USBR) and United States Army Corps of Engineers (USACE) is widely used in the industry for design of standardised stilling basins with chute blocks, baffle blocks and special end sills. The established guidance is largely directed towards engineering efficiency and does not give due consideration to the safety of the structures being designed. Existing guidance needs to be considered in light of the safety requirements set out in **Chapter 10**.

UK weirs tend to be of relatively low height and Frs for supercritical flows entering stilling basins are usually correspondingly low. This can result in poor energy dissipation at the structure and relatively high residual energy (up to 50 per cent), and travelling waves downstream of hydraulic jumps formed at weirs. At many sites this results in deep weir pools, erosion to downstream banks and limitations on gate operation during low flow. Stilling basins can be designed to mitigate this (see Peterka, 1984), however, the benefits of active stilling should be balanced against the dangers presented to those in the water. It is worth considering that the function of a stilling basin is to reduce and localise the scour in a position where it can be controlled and is not harmful to the weir and downstream channel, not to eliminate it (Novak *et al*, 2007).

Thames Conservancy (1962) notes: *"In certain cases the length of structure required to include the whole of the turbulence created by the jump becomes impractically long and it may be considered sufficient to include only one half or two thirds of the calculated jump length [...] This economy is allowable particularly where the discharge from the weir is into an existing weir pool"*.

This statement is not necessarily one that should be followed, however, it gives credence to the idea that energy dissipation and in particular scour protection for weirs is an area that depends on the weir owner's approach to capital expenditure, maintenance, monitoring and risk, as much as assessment of physical processes. In the following section it is suggested that the weir foundation should extend below the anticipated scour depth, so that the structure is safe regardless of the effectiveness of energy dissipation, scour protection and ongoing monitoring and maintenance.

General design of stilling basins is covered by a number of civil engineering hydraulics textbooks (eg Novak *et al*, 2007). Specific guidance for individual basin types is also readily available (eg USDotI, 1987). Broadly speaking, initial sizing can be carried out as follows.

- Using the upstream and downstream rating curves, and anticipated operating rules for gated weirs, it will be possible for the designer to assess hydraulic conditions upstream and downstream of the energy dissipation structure for a variety of flow conditions. To do this a downstream tailwater rating curve will need to be derived (the reader is referred to relevant hydraulic textbooks). A set of critical design situations can be defined. Note that the critical hydraulic condition for energy dissipation may not be at the design flow. Partial gate openings should also be considered.
- It should be noted that the critical condition for energy dissipation may be a low tailwater level. Degradation of the bed downstream of the weir may occur after construction or as part of long-term morphological change, which should be taken into account when determining the tailwater rating curve. In addition, whereas assuming a high channel roughness is conservative in flood modelling

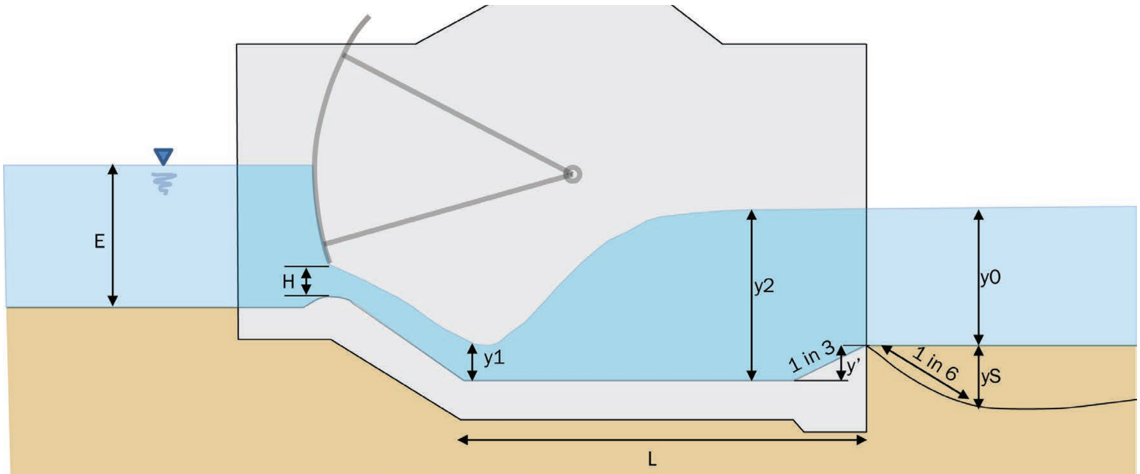


Figure 13.7 **Hydraulic jump stilling basin**

it could be unsafe for developing the tailwater rating curve, where instead assuming a low channel roughness is a conservative approach.

- The depth of the stilling basin is chosen to produce a submerged jump, ie lowered below the river bed so that the downstream water depth is greater than the depth of the hydraulic jump in the basin (by a chosen factor of safety, FoS), as shown in **Figure 13.7**.
- The length of the basin is then defined as a multiple, *K*, of the sequent depth.
- A simple end sill with a 1:3 slope is usually appropriate and functions to direct flow leaving the basin upwards, discouraging scour immediately downstream of the basin.

13.7 SCOUR AND SCOUR PROTECTION

13.7.1 Scour

At weirs and downstream of stilling basins, flow conditions are highly turbulent and if left unchecked, will scour the river bed until a weir pool of sufficient volume develops to dissipate energy released from the head drop at the weir. The large weir pools and shoals that can be seen downstream of many weirs in the UK are, in many cases, of significant environmental value, but can require expensive bank protection and channel maintenance over time. Excessive erosion can be avoided by designing sufficient stilling provision, but engineering design should consider a balance between the cost of the weir structure, the risk to public safety, which can be posed by a highly effective stilling basin, and the cost of downstream bank protection.

Development of significant scour is of concern to the designer principally because over time not only can it endanger the weir structure, but it can also result in damage to downstream infrastructure, bank protection and land adjacent to the river.

Different bed materials scour at different rates, with loose granular material having a low resistance to scour. It is important to realise that cemented or cohesive soils will scour to the same depths as loose material, over a longer period of time, but usually well within the design life of a weir. Scour may reach its maximum depth in sand within a few hours, cohesive bed materials in days, glacial tills, sandstones and shale within months, limestone in years and dense granites in centuries (TSO, 1994).

Failure mechanisms due to scour can include:

- Undermining of the weir or river bank, leading to settlement, rotation or sliding and ultimately failure of critical structures.
- Combined scour and piping failure, whereby the seepage path length under the weir is reduced by scouring to the point at which piping failure occurs.

As noted in **Section 11.6**, a general principle that should be adopted is that scour protection should not be relied upon to ensure the structural integrity or stability of a weir. On this basis, foundations should be designed to be deeper than the anticipated scour depth and all stream bed material in the scour prism above the total scour depth should not be relied upon for bearing or lateral support, or for resistance to seepage. In practice this typically means designing the embedment of the downstream cut-off or toe at least to a point below the calculated scour depth.

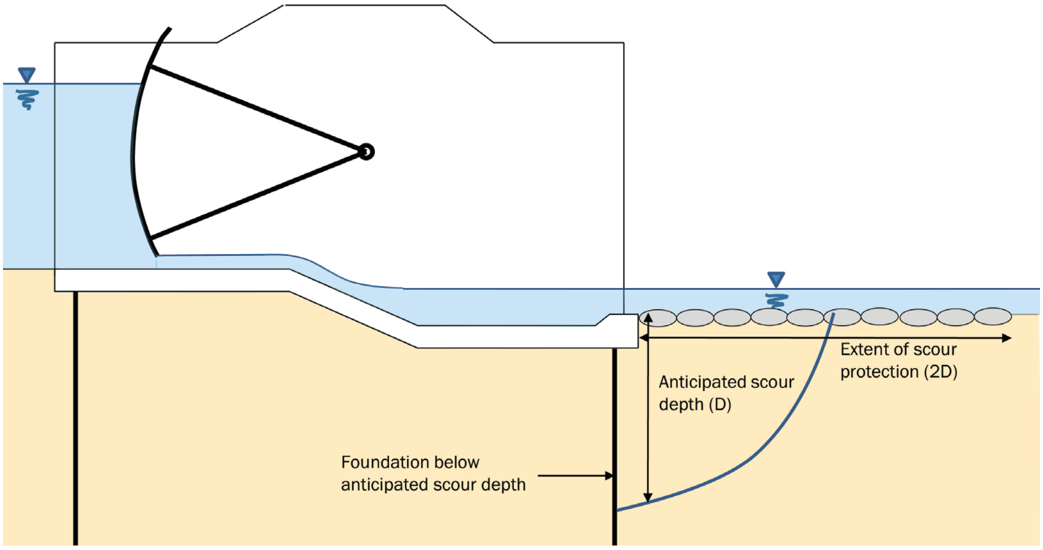


Figure 13.8 *Foundation depth and anticipated scour depth*

Several methods exist for assessing scour depths downstream of a weir. These are summarised in Kirby *et al* (2015), which provides both a method of assessment and also refers to further detailed guidance. Different methods can give significantly different scour depths, so selecting a design scour depth usually involves a degree of expert judgement and observation of ongoing scour processes in the area (see **Figure 13.8**).

13.7.2 Scour protection

For weirs founded on erodible material (ie anything other than hard rock) protection should be provided against scour of the downstream channel. Depending on the channel geometry, hydraulic conditions and approach to the weir, scour protection may also be required upstream of the structure. Design of protection can be more complex for compound structures, where velocity differences across a structure can lead to eddies, and for wide structures where cross-flows can generate eddies.

The distance downstream over which protection should be provided depends on the transition between flow conditions in the stilling basin or apron and conditions in the downstream channel. Kirby *et al* (2015) provides a general guide to the specification of scour protection at hydraulic structures and contains reference to more detailed guidance. The guide notes that common sense and experience should be used to determine the extent of scour protection, but as a preliminary advice, the protection should extend downstream for about five times the head difference across the structure. Additional recommendations for scour protection are given in Aisenbrey *et al* (1978) (see **Figure 13.9**).

For existing structures, the condition of existing scour protection and the presence of scour holes should be identified during initial bathymetric surveys. Remedial works should aim to replenish the scour protection where required, but also to identify if there are any underlying reasons for the development of scour holes or movement of the downstream protection. Such reasons might include biased operation of the weir in one section of the channel, a lack of inspection or maintenance following major floods, inappropriately sized scour protection, subsurface erosion (piping) or inadequate stilling provision. Steel sheet piling can often be required to halt erosion damage and commonly to provide protection along the downstream edge of the weir apron. High slump concrete and grouting through the apron can be required to infill any voiding that extends underneath the weir. The presence of a deep weir pool can also have significant implications for the design of temporary works and bathymetric information should therefore be provided to tendering contractors so that appropriate provisions can be made to deal with the prevailing bed levels downstream of the weir.

13.8 DESIGN REFERENCES FOR SPECIFIC WEIR FUNCTIONS

13.8.1 Flood risk management

High level guidance on the design of flood storage and control devices (including diversion weirs and gated control structures) is given in Ackers *et al* (2009).

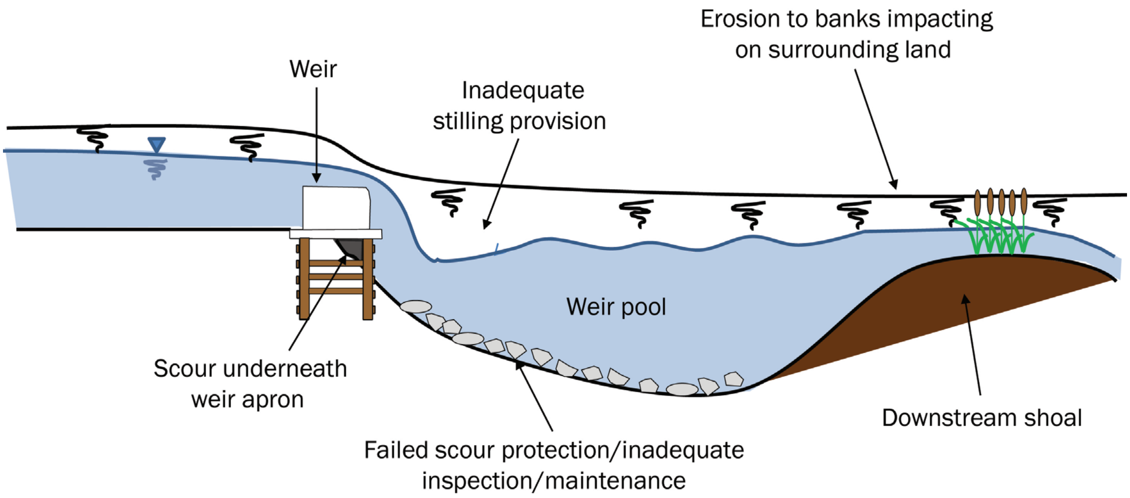


Figure 13.9 Typical scour issues at an existing weir

Box 13.1 Gated weir replcacement, Knostrop weir, Leeds

Knostrop weir on the River Calder in Leeds is due to be replaced with a gated weir as part of works to reduce flood risk to central Leeds. Due to failure of 'summer boards' on the crest of the old weir, flow over the weir favoured the left-hand side and a significant scour hole developed in the sand, gravel, mudstone and sandstone material immediately downstream of the weir. A 40 m length of an old railway bridge abutment wall is undermined with the scour hole extending three metres into the bank under the wall in places. Before works to remove the old weir could be carried out, the wall had to be underpinned. A physical hydraulic model of the weir was used to predict flow velocities and confirm likely scour depths. Following repairs to the wall, rip-rap scour protection was provided for the new weir and in front of the wall.

Environment Agency (2009) provides guidance on designing inlet weirs for flood storage areas.

Hall *et al* (1992) gives practical guidance on the design of storage reservoirs, including flow control devices, although some sections are out-of-date. The Environment Agency is currently preparing guidance on the design, operation and adaptation of flood storage reservoirs, which is in press. Winter *et al* (2010) gives guidance on the design of stepped masonry spillways. Design standards for detailed design are provided by the Eurocodes.

13.8.2 Navigation

PIANC (2006) performed a comprehensive review of modern design technologies, design tools, and recent research used to design and build structures controlling water level and flow in rivers, waterways, and ports (for navigation and flood protection). The working group considered regulatory structures of river control weirs and storm surge barriers, focusing on the gate design. For detailed information, the reader is also referred to several comprehensive textbooks that are available describing the design of hydraulic gates. For example, Lewin (2001) and Erbisti (2003) describe the principal aspects of the design, manufacture, installation and operation of hydraulic gates. For feasibility level comparative studies, the weight (and consequently cost) of steel gates and embedded parts can be estimated using the guidance in Erbisti (2003).

13.8.3 Flow measurement

Broadly speaking weirs specifically designed for flow gauging are of predetermined geometry. However, the designer must size the weir to ensure that flow conditions are modular over a suitable range of flows so that the stage discharge relationship can be easily used for flow measurement. Gauging weirs should be located in straight reaches of river, with appropriate river training works to promote streamlined approach conditions.

- **Short-crested weirs:** overflow structures at which the streamline curvature above the weir crest has a significant effect on the stage-discharge relationship at the structure (Bos, 1989). The structural form of the discharge equations for short-crested weirs are presented in various International Organization for Standardization (ISO) standards and Bos (1989), with the derivation of coefficients specific to the type of structure involved.
- **V-notch weirs:** a triangular shaped control section is useful where the structure is used for flow measurement. Under low flow conditions, the structure is more sensitive to variations in flow, whereas under high flow conditions the weir crest is wide and the backwater impact of the structure is reduced. Specific dimensions and design requirements for V-notch weirs for flow measurement functions are detailed in Bos (1989).
- **Triangular profile or 'Crump' weirs:** these structures have inclined upstream and downstream faces with an intersection at a horizontal crest line across the channel. The standard gradients for the structure are 1:2 on the upstream face and 1:5 on the downstream face. The principal use of the structure is for flow gauging.
- **Triangular profile flat-V weirs:** this type of structure applies a triangular profile structure but has a lowered mid-point to the crest. Standard angles for the cross-slopes to the mid-point of the crest and the upstream and downstream faces are usually applied as detailed in Bos (1989).
- **Broad-crested weirs:** the application of a broad-crested weir for flow measurement is dependent on the weir crest height above the channel bed being sufficient to generate critical depth at a control section on the crest. Where this occurs and the length of the weir crest in the direction of flow causes the streamlines to be practically straight and parallel, a head-discharge relationship can be derived (Bos, 1989).

Requirements for the design of flow measuring weirs are set out in a range of ISO documents, covering UK and International Standards, for the measurement of liquid flow in open channels, including:

- ISO 4374:1990 deals with the measurement of flow in rivers and artificial channels under steady flow conditions using round-nose horizontal broad-crested weirs. The flow conditions considered are limited to steady flows which are uniquely dependent on the upstream head. Drowned flows, which depend on downstream as well as upstream levels, are not covered.
- ISO 4360:2008 details the specific requirements for the installation of Crump weirs.
- ISO 8333:1985 specifies a method for the measurement of subcritical flow in small rivers and artificial channels using V-shaped broad-crested weirs.

White *et al* (2005) presents research to extend the scope of the ISO documents to include design features which would aid the migration of fish without significantly compromising flow measurement accuracy. ISO 26906:2015 provides guidance for fish passes at flow measurement structures.

Further information and design guidance for common types of gauging weir can be found in several civil engineering hydraulics textbooks, including Bos (1989), and Novak (2007) which offers design flow charts and worked examples which are a useful starting point for design.

Box 13.2 Horrabridge Weir, Dartmoor

Horrabridge Weir is a predominantly masonry weir located within Dartmoor National Park. It was once part of a mill leat system and was subsequently re-engineered to become a flood gauging weir and part of a small flood alleviation scheme. The weir was altered in 2014 to improve the efficacy of the existing fish pass, to provide an eel pass and to carry out repairs and desilting works to the existing structure. Weir repairs were conducted in the same style as the original construction, using reclaimed stone on site to clad the new concrete fish pass. The upstream crest of the fish pass weir provides the gauge for low flows and so during the hydraulic design of the new fish pass, care was taken not to drown the upstream crest during normal flows. This requirement resulted in a need to deviate from normally accepted limits for fish pass design, however an acceptable solution was found that improved the existing pass without compromising the longstanding gauging record.

13.8.4 Channel stabilisation

Grade control weirs can be constructed downstream of existing structures such as bridges considered to be at risk from bed degradation, particularly where a step reduction in bed level is cutting its way upstream (termed a knick-point recession, see **Figure 3.3**). If these types of change are detected, a longitudinal survey should be carried out to quantify the likely change in bed level that will occur when the adjustment in channel gradient and depth reaches the site. If the magnitude of the change cannot be accommodated in the design of the structure, measures to stabilise the channel profile should be adopted (eg constructing a weir to prevent a knick-point progressing farther upstream).

Barkdoll *et al* (2007) and Kirby *et al* (2015) provide examples of these structures, alongside alternative measures for bridge protection, which do not involve construction of a weir.

13.8.5 Environmental enhancement

Environment Agency (1999) good practice guidelines for rivers and wetlands cover the use of low weirs for environmental enhancement. The guidelines discuss the environmental benefits and limitations of different material types for weir construction, but pre-date the WFD and so are not up-to-date.

Guidance on the use of weirs for wetlands is given by USACE (1993). Ellis *et al* (2003) discusses the types of wetland and provides some advice on maintenance of constructed wetlands. Design guidance for small in-line weirs and side weirs is provided by Kraatz and Mahajan (1975) and May *et al* (2003) respectively. RSPB (2008) gives practical guidance on simple water management structures for conservation while Streamlife (2009) provides information on sluice operating protocols to balance water level management with conservation.

13.8.6 Fish passage

Several good practice guides on the design of weirs to prevent harm to fish and the design of fish and eel passes, and smolt chutes are summarised here.

- Armstrong *et al* (2010) provides comprehensive guidance on the legal requirements relating to fish passage in England and Wales, factors affecting fish pass selection, types of fish pass, other fish passage solutions, fish passage at particular structure types such as gauging station, monitoring and maintenance.
- SEPA (2015b) provides concise guidance for developers of run-of-river hydropower schemes on the design of weirs and plunge pools to prevent harm to fish passing downstream over the weir, as well as the choice of fish pass.
- Environment Agency (2011b) provides information on the design and implementation of passes at weirs, tidal gates and sluices. The document discusses how to prioritise solutions to meet legal requirements, climbing substrates, bristle eel passes and treatments at non-gauging weirs. It also gives advice on tidal fish gates and self-regulating tidal flaps and gates.
- Other older but useful references include Larinier *et al* (2002) and FAO and DVWK (2002).
- The RRC in the UK and the European Centre for River Restoration (ECRR) both house substantial depositories of river restoration texts including references specifically dealing with fish passage and improving connectivity (RRC, 2013).
- A by-wash for downstream migrating smolts (young fish) may be required at abstraction points. These should comprise a smooth and safe conduit that will not cause harm to fish, with an inlet near the obstruction and a discharge point to deep water. The flow should accelerate smoothly into the conduit, which should be covered to avoid predation, with suitable lighting without sudden interfaces between light and dark. Guidance on downstream by-washes is available in NRW (2014a).
- The construction of a fish pass provides an opportunity to construct a conjunctive fish pass, or a fish pass that doubles as a canoe chute. The provision of a wide fish pass with sufficient depth of water over the baffles allows paddlers to shoot the fish pass without getting out of their craft, while also allowing fish to migrate. There can be conflicts between the two functions and an alternative is to construct the canoe chute and fish pass separately, next to each other. Guidance is given in Armstrong *et al* (2010).

13.8.7 Canoeists

Some existing weir structures are popular canoeist features and the eddies, stoppers and waves formed downstream of a weir can be regularly used by many people. Where works are proposed to an existing weir that is used for canoeing, it is important that the proposed changes are discussed with recreational users and where possible hydraulic features that are valuable are retained or enhanced. Hydraulic conditions that are potentially unsafe to those in the water should be identified and where possible removed by design.

13.8.8 Abstraction

Where a weir is required as part of an abstraction scheme, siting of the weir should be carefully considered to minimise the impacts on geomorphological processes and it should always incorporate a fish pass. NRW are currently producing a hydropower design guide that includes recommendations for optimal siting of weir structures.

Hydraulic design for recreational features is not well documented and specialist advice and physical or numerical modelling is usually required. Versatility in the design is key, given that variable flows, gate openings and tailwater conditions can greatly affect a play-wave feature. Users will also have different requirements and preferences (training, competition etc) so some adjustability is desirable. With some thought many existing weirs can be adapted into excellent features, sometimes at very little cost.

Figure 13.10 Canoeing at Hurley on Thames

Box 13.3 Case study: Mapledurham weir 'E' (courtesy Andy Laird, Engineering Paddler Designs Limited)

A new large radial gate at Mapledurham weir 'E' on the River Thames was installed to replace the old timber paddle weir. When the gate is opened, the discharge forms fast sheet flow for low gate openings and a damaging wave train for higher gate openings. So the gate is only operated during very high flows, where tailwater levels enhance energy dissipation. As an experimental feature, rails were installed in the downstream apron to enable a deployable mobile whitewater obstacle system to be attached for periodic recreational use. The blocs result in enhanced energy dissipation and deeper flow, which is of interest as a play-wave for canoeing. The versatility of the block system and ability to vary the gate opening allowed a useable wave to be formed by trial and error, and indeed the wave to be adapted as required. Ventures of this type can convert a single-use structure into something of great value to the local community (canoe clubs and other activity clubs such as scouting groups). However, before a viable recreational feature can be installed and used, there weir operation, safety, liability and insurance may need to be addressed.

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ISO 8368:1999 *Hydrometric determinations. Flow measurements in open channels using structures. Guidelines for selection of structure*

ISO 14139:2000 *Hydrometric determinations. Flow measurements in open channels using structures. Compound gauging structures*

ISO 26906:2015 *Hydrometry. Fishpasses at flow measurement structures*

FURTHER READING

Statutes

Standards

ISO

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14 Foundations and geotechnical design

14.1 INTRODUCTION

This chapter discusses key considerations in the location and design of a weir foundation and superstructure and in the selection of the materials used for construction. A weir will be subjected to very onerous conditions over the course of a long design life, some of which may not be immediately apparent. So it is important that the material and engineering design are suitably robust to avoid premature failure of the structure, but also that other aspects such as visual appearance and sustainable material use are given due consideration.

As previously noted, all design should be carried out with the avoidance of risk in mind and following a hierarchy of risk control. In the UK, the designer must comply with duties set out in CDM 2015 and follow the measures given in the guidance that accompanies the Regulations.

14.2 WEIR LOCATION

An important early consideration in the design of a weir is locating the structure in an optimum location. Considerations for macro-scale location of a weir were introduced in **Section 5.5.2**. Considerations include topography and geomorphology of the catchment, flooding of upstream infrastructure, environmental considerations, geology of the foundations, material availability, hydrology, site access and ease of river diversion during construction. These factors should be balanced to find the most economic site for safe construction of the weir to suit the project requirements. Further coverage of this topic is given in the dam literature (eg USBR, 1995), which is in the most part applicable to weirs.

In the UK, infrastructure surrounding a new weir may have developed over many hundreds of years. In urban areas, the selection of a suitable weir site usually relates to small-scale adjustments within a fairly prescribed weir location, often associated with the site of an existing weir that is to be replaced.

Typical options for the micro-scale location of a weir are shown in **Figure 14.1**.

Where the new weir replaces an old weir, moving the weir footprint may make construction more straightforward, because foundations and bed protection associated with the old weir can be avoided.

A site downstream of the existing weir (location 1 in **Figure 14.1**) might be selected because water levels are typically lower and the old weir can be used for regulation of the river during construction. However, altering the location of the weir may mean that the alignment and height of approaching river banks, embankments and roads also need to be adjusted. A downstream site will result in higher groundwater levels for the reach of river between the new and the old weir. This can be a problem if existing infrastructure has been developed under the prevailing groundwater conditions, see Hill (2006). A downstream site may also be uneconomic if a wide and deep weir pool is already present downstream of the existing weir.

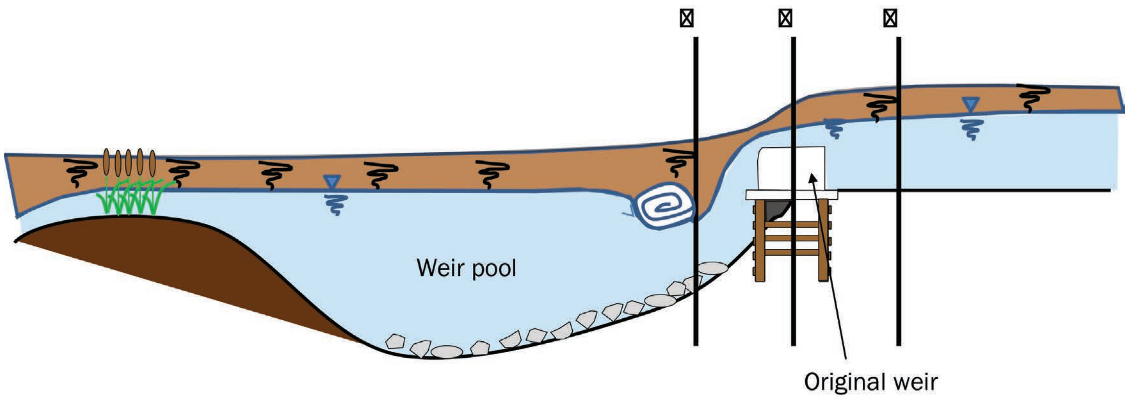


Figure 14.1 Location of a new replacement weir

A location on-line with the existing weir (location 2 in **Figure 14.1**) might be selected where the surrounding infrastructure, topography or land ownership dictates that the existing weir site should be reused. In this case, the uncertainties of building directly over the existing structure (as discussed in **Section 5.4**) should also be considered.

An upstream site (location 3 in **Figure 14.1**) might be selected to avoid a deep weir pool, or significant obstructions resulting from scour protection or the existing weir structure. An upstream site typically involves more complex temporary works, including the removal of a greater proportion of the old weir structure to sufficiently lower the downstream bed level.

14.3 FOUNDATIONS

14.3.1 Introduction

Weirs are a bit like icebergs – most of the structure remains unseen throughout their life. Also, the unseen portion is largely inaccessible and so should be engineered to remain durable with little maintenance. Weir foundations differ from conventional building foundations as they are acted upon by destabilising water forces that are relatively large when compared to the foundation weight. Other processes such as scour and piping (hydraulic fracture) and the requirement to consider temporary works as an integral part of the permanent works design, make the design of a weir foundations a highly interlinked exercise, requiring the co-ordination of a number of competing design threads.

As noted in **Chapter 2**, due to the hazard involved in dam operation, the design of dams (and consequently many river weirs) has in the past been carried out to well-established rules that vary across the component under consideration. BS EN 1990:2002 states: *"For the design of special construction works (eg nuclear installations, dams, etc.), other provisions than those in EN 1990 to EN 1999 might be necessary"*.

Eurocodes use a limit state approach to design, however the use of the limit state design is not common practice among dam engineers (Caldeira, 2013). This can lead to difficulties in establishing a consistent approach for the entire structure (PIANC, 2006) or in meeting the requirement to demonstrate code-compliant weir design to national or international standards.

While guidelines to assist the designer in applying limit state design to new maritime and waterways works have been prepared in France (Moine *et al*, 2000), practical guidance for the consistent application of limit state and partial factor design (and in particular Eurocode design) for weirs is fairly disparate. In addition, it is generally considered alongside other non-coded guidance, which is accepted within the hydraulic structures community as established practice for the design of safe structures.

A unified structural design approach for river weirs is beyond the scope of this guide, so the designer should carefully select relevant guidance for design and ensure that the approaches used are compatible across the structure. In practice, this currently entails meeting the criteria for both Eurocode limit state design as well as other widely accepted criteria. This guide gives a clear set of signposts to the relevant criteria that should be considered in parallel to design to Eurocode (**Table 14.1**). Pickles *et al* (2014) provides a useful framework for the application of BS EN 1997 Eurocode 7 (EC7) to river structures (in the form of flood embankments), however the guidance is not wholly applicable to river weirs.

14.3.2 General design considerations

The low head weirs that are typically constructed in the UK can, in general, be considered as spread foundations subject to special hydraulic actions because they impound water on one side. EC7 lists a number of standard considerations for the design of a spread foundation including checking that:

- there is sufficient stiffness to prevent unacceptable settlement
- the ground has adequate capacity to withstand vertical actions
- there is sufficient sliding resistance to withstand horizontal and inclined actions.

These aspects must be considered during the design of a weir and the reader is referred to EC7 and relevant literature (eg Bond and Harris, 2008) for discussion of a general design approach.

Table 14.1 Design criteria: ready reference

Element	Eurocode standard	Other standards	Guidance and research
Applied actions	BS EN 1991-1-6:2005	BA 59/94[1] BD 37/01[2]	Pickles *et al* (2014)
Design floods	BS EN 1991-1-6:2005	BA 59/94 Network Rail (2011)	
Limit states	BS EN 1990:2002	BA 59/94 Network Rail (2004)	
Partial factors	BS EN 1991-1-6:2005 BS EN 1997-1 Annex A	BA 59/94	
Debris and vessel impact	None	BA 59/94	Haehnel and Daly (2004) Network Rail (2011) Parola *et al* (2000)
Drag	BS EN 1991-1-6:2005	BA 59/94	Parke and Hewson (2008) Kerenyi *et al* (2009)
Lift	None	None	Kerenyi *et al* (2009)
Static equilibrium (overturning, sliding)			Ebeling *et al* (2000) USACE (2005)
Scour	None		Kirby *et al*(2015)
Hydraulic fracture (piping)	BS EN 1997-1:2004+A1:2013 (2.4.7.5)*		Khosla *et al* (1981) Bond and Harris (2008)

Note

* Expression (2.9b) does not provide a sufficient level of reliability for weir design.

For information only – not to be used for design:

1 TSO (1994).

2 TSO (2001).

14.3.3 Weir specific considerations

Special considerations that result from the fact that the weir retains water are:

- Abnormally high destabilising actions, due to the retained water and abnormally low stabilising actions, due to the distribution of uplift pressures under the foundation.
- Checking that there is adequate resistance to seepage and hydraulic fracture (piping).

It is usually most straightforward to consider these aspects in the reverse order to that in this bullet list, as shown in the process diagram in **Figure 7.2**.

14.3.4 Design situations

BS EN 1990:2002 (clause 1.5.2.2) states that design situations are: *"Sets of physical conditions representing the real conditions occurring during a certain time interval for which the design will demonstrate that relevant limit states are not exceeded"*.

In determining the design situations to be considered for the weir it is important to understand how the structure will be acted upon at various flow rates and water levels. Once the hydraulic capacity and general hydraulic arrangement of the weir has been selected, as described in **Section 13.3**, the response of the river can be determined across a range of flows. So the designer can define hydraulic design situations for the structural analysis of the weir and associated structures. It is important to note that both the upstream and downstream water levels will vary with flow and so it is usual to directly assess water levels and water pressures, rather than to factor characteristic water levels.

Out-of-bank flow is not usually the most onerous load case on the weir structure, but may place excessive demand upon structures associated with the weir such as approach embankments or walls or damage to associated facilities such as telemetry equipment. Drawdown of a flood can also place out of the ordinary demand upon these structures. However, the most onerous hydraulic loading upon a weir structure may well be during low-flow conditions where water levels downstream of the weir are likely to be low and consequently the differential head across the structure will be

high (Challa, 2006). The variation in water levels with flow will depend on the weir, the channel geometry and the presence of other obstructions to flow in the channel (such as bridges). This will vary from site to site.Typical situations for low and high flows are shown in **Figure 14.2**.

Changes in the relative uplift forces acting on a weir should be considered during stanking-off of weirs or parts of weirs. Reducing the weight of water on the weir substructure when installing a cofferdam (eg for gate replacement) could increase the destabilising uplift forces, particularly if there is a pre-existing piping issue.

14.3.5 Seepage, piping and uplift

Hydraulic failure of a weir or barrage foundation can either broadly occur by two mechanisms. A piping failure occurs when the hydraulic gradient in the foundation material is sufficient to cause washout of material, undermining and ultimately collapse of the structure. Failure by uplift can occur when the pressure exerted by water seeping under the structure is sufficient to lift the structure vertically or reduce effective vertical stress under the structure to a degree that it becomes unstable. Flotation can be a risk under high groundwater levels, even without piping.

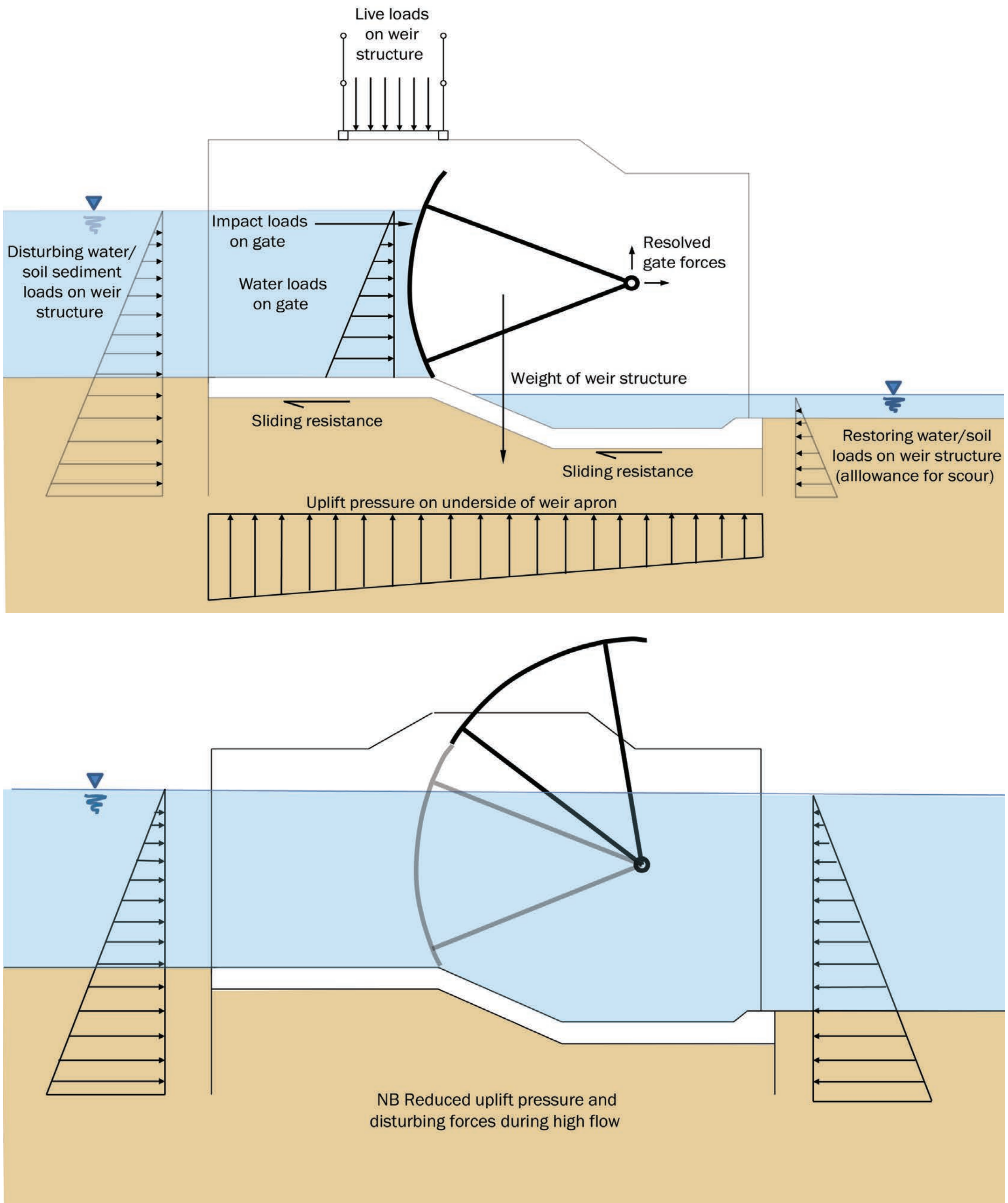


Figure 14.2 ***Determining design situations (typical situations for high flow, low flow and construction)***

With this in mind, weir foundation design is generally split into two broad categories:

1 **Permeable foundation:** where a weir is founded on a permeable foundation, seepage and piping failure should be considered. The 'exit gradient' is the hydraulic gradient of the seepage flow under the base of the weir floor. The term exit is used because the critical position of the hydraulic gradient is invariably at the downstream toe of a structure, ie the point at which the seepage exits the foundation. If the exit gradient is too large 'boiling' of the foundation surface is initiated as soil is washed away by the percolating water. The flow concentrates into the resulting depression removing more soil and creating progressive backwards scour, which may eventually undermine the barrage structure. This mode of failure is called 'piping'.

2 **Alluvial soils** the critical exit gradient, ie the point at which boiling is initiated, is around unity. However, because of the local variations in the foundation hydraulic gradient caused by inconsistencies in the soil matrix, the inability to inspect the many potential seepage paths, and the catastrophic nature of any potential failure mechanism, relatively high FoS are generally recommended. With a FoS of around 5.5, typical permissible exit gradients are listed in **Table 14.2**.

Table 14.2 Typical acceptable exit gradients

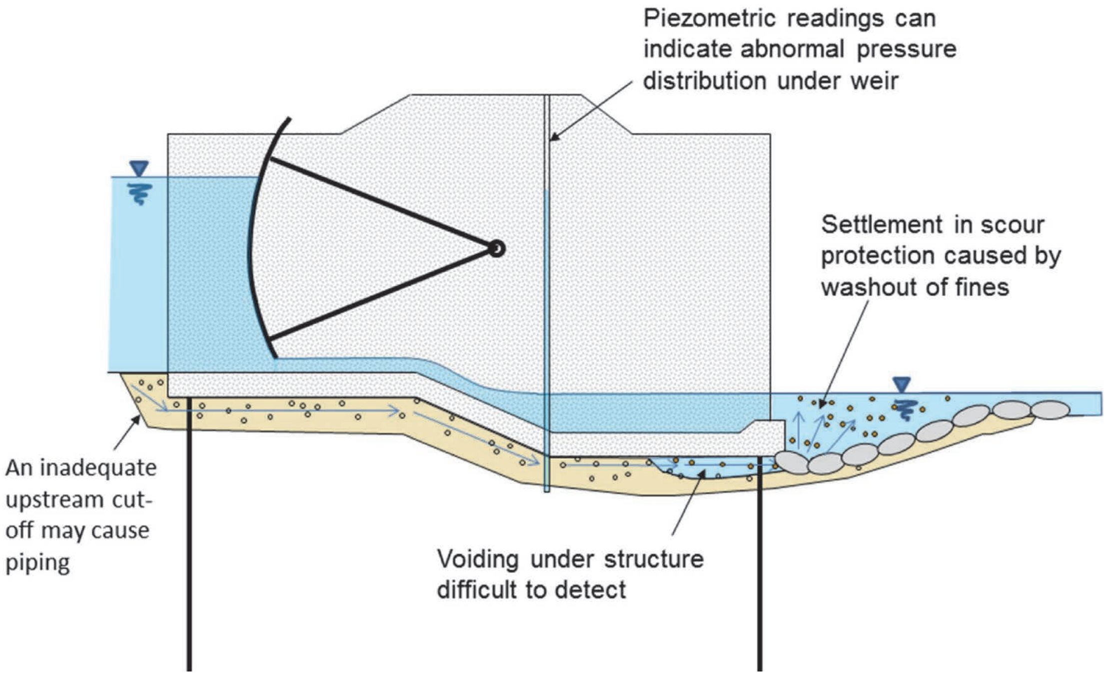
Material	Permissible exit gradient
Fine sand	1:6 to 1:7
Coarse sand	1:5 to 1:6
Shingle	1:4 to 1:5

Two methods of checking hydraulic failure are given in BS EN 1997-1:2004+A1:2013 (Clause 2.4.7.5), one based upon comparing destabilising pore water pressure to the design stabilising vertical stress and the other comparing the design destabilising seepage force to the design stabilizing submerged weight. Both of these criteria are applied at the base of the soil column under consideration. The latter does not provide sufficient reliability for weir design (for further detail see Bond and Harris, 2004), while the former provides equivalent global FoS which are lower than usually considered acceptable. So it is prudent to carry out a traditional global FoS approach in parallel to Eurocode design.

The differential head across the weir is fixed for a given design, so to reduce hydraulic gradients to the required level, the seepage path must be lengthened. This can be achieved by lengthening the impermeable floor of the weir (both upstream and downstream of the weir crest) or by providing impermeable barriers or 'seepage cut-offs' below

Seepage around the side of a weir can cause washout of fine material. Sinkholes in the bank are an indication that this process is occurring. Here, an irrigation weir (canal head regulator) in Helmand Province, Afghanistan, shows signs of significant washout of material behind the downstream wing wall.

Figure 14.3 Indications of material washout around an existing weir



Here a side sluice on a canal that is at the end of its useful life. Significant seepage and material washout has caused settlement of the structure. Large quantities of water were flowing under the weir apron and the brick structure was in places close to collapse.

Figure 14.4 Indications of material washout

the weir. In UK alluvial soils, seepage cut-offs are typically from steel sheet piles, which are also commonly used in temporary works to dewater the weir site. Slurry walls, grout curtains, secant piles and other techniques can also be considered (**Figure 14.5**). Cut-off structures are also beneficial because they prevent scour of material from underneath the weir (see **Section 13.7**).

Although most seepage analysis for weirs is done in two dimensions, the designer should also appreciate that seepage is a three-dimensional problem and lateral cut-offs may be required to prevent circumnavigation of cut-offs under the weir. Where weir geometry is non-typical (eg gate bays staggered longitudinally down the channel) care should be taken to ensure that shortened seepage paths do not exist laterally across the structure.

Manually-derived flow nets and desktop designs of cut-off geometry were commonly used in the past to estimate hydraulic gradients under a weir. This practice has now largely been replaced by finite element analysis (FEA) for all but the simplest structures or for initial sizing (**Figure 14.6**). This technique allows the designer to relatively quickly

To prevent separation and seepage along the interface between cut-offs and the weir structure it is important that the interface is designed to prevent or accommodate relative movement. In the photograph, sheet-piling used for a downstream toe has been tied into the reinforcing steel for the weir apron. In this case a steel angle has been welded to the pile and the reinforcement tied around it. Any lifting holes in the piles should also be blanked off to prevent the escape of fine material from under the weir.

Figure 14.5 Interface of cut-off with the weir structure

alter the length of the weir apron and cut-offs to give the desired exit gradients. Sensitivity to permeability and anisotropy in permeability can also be quickly understood using these tools.

14.3.6 Other foundation considerations

Having sized the weir foundation to give acceptable hydraulic exit gradients, the designer should check the foundation for sufficient resistance to sliding, overturning and bearing capacity failure and to ensure that the anticipated settlement is within acceptable limits. While the reader is referred to one of the numerous good geotechnical guides for this analysis, the following are areas that require specific consideration for weir design.

14.3.7 Uplift

Uplift pressures reduce effective stresses under the weir and resistance to sliding can be significantly reduced. This can influence the design, particularly as passive resistance from material downstream of the weir should be ignored due to the potential for scour. An uplift pressure distribution should be derived from a finite element seepage model.

Most weirs of the geometry encountered in the UK are designed to resist uplift as gravity structures (as opposed to bending in the slab between heavy piers). So adding weight to the foundation is a common requirement and this is usually achieved by increasing the dimensions of the downstream apron slab. Often, it is most efficient to do this with a mass concrete foundation covered by a thinner layer of reinforced concrete.

Some larger structures also relieve pressures under the structure through drainage, although this is not often optimal for low head weirs in the UK. If drainage is considered, it is not usually acceptable to rely upon it to reduce pressures for design. Gravity drainage can be rendered ineffective by rising tailwater levels or blockage and pumped drainage can cease to function during power cuts.

The worst permanent case for uplift is likely to be in low-flow conditions when the water level difference between upstream and downstream is highest, and there is little weight of water on the downstream apron. Changes in the relative uplift forces acting on a weir should be considered during stanking-off of weirs or parts of weirs. Reducing the weight of water on the weir substructure when installing a cofferdam (ie for gate replacement) could increase the destabilising uplift forces, particularly if there is a pre-existing piping. In extreme cases, the uplift force on the apron could cause it to lift and crack. So it is common to limit the length of weir that can be dewatered at any one time.

For higher flow conditions, when considering the vertical restoring force of water downstream of the weir, the position of the hydraulic jump should be checked. Where energy levels are high enough to sweep the jump to the downstream end of the stilling basin, the weight of water on the upstream end of the stilling basin slab may be very low.

Although it is not a requirement under EC7, it is usual practice to design dams and hydraulic structures for a zero tension condition at interface between the foundation and the ground and for horizontal planes up the structure.

During construction, when the works have been

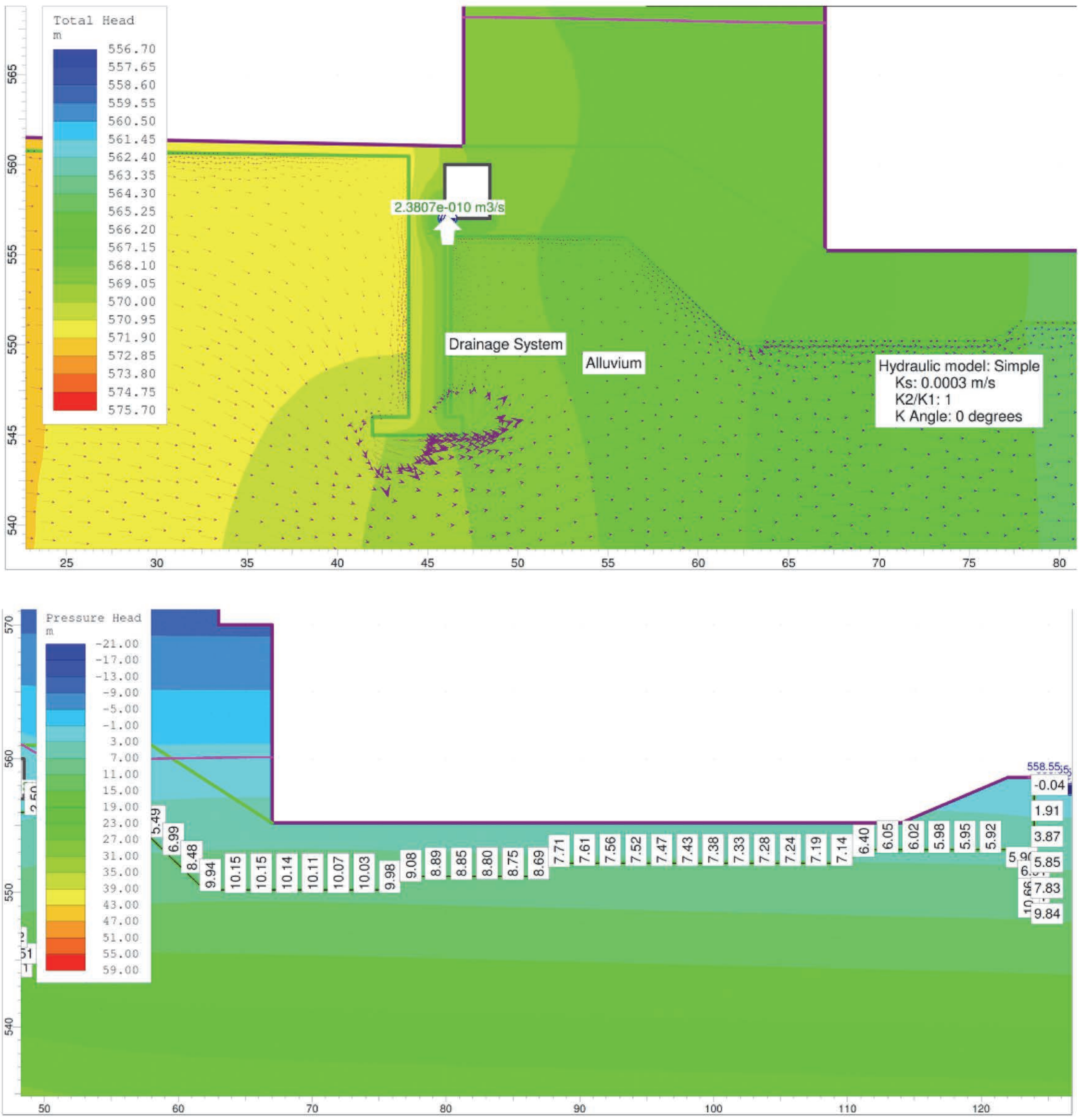


Figure 14.6 ***Determining hydraulic gradients and uplift pressures using FEA***

dewatered and excavation has been carried out for the weir foundation, pumping will usually be required before and during placement of the weir apron to prevent uplift pressures and seepage flows from disturbing the concrete.

14.3.8 Heave and swelling

Weir construction can involve removal of a significant amount of overburden to found the stilling basin. In over-consolidated clay foundations, removal of the confining stress and exposure of the clay to water can result in heave and swelling respectively, which can damage an overlying weir foundation. In these cases the weir slab should be designed to be of sufficient weight to resist long-term heave.

14.3.9 Settlement

In general, weir structures impose a relatively low pressure on their foundations, and so differential settlement leading to deformation and cracking is unlikely to be a problem, providing there is sufficient protection to avoid the loss of material from under the weir.

If there are weak layers in the foundation (eg peat), it may be necessary to remove them or, in extreme circumstances, to support the weir on piles or otherwise improve the ground. Differential settlement is of particular concern for gated weirs, as even small movements can prevent the gates from operating. If movement joints are required in the weir structure they should be located between gate bays where possible, rather than within the bay.

In the early days of weir construction, when construction methods were limited by available technology, the use of timber piles to support weirs on weak alluvial soils was quite common. This may be a key factor in the design of major remedial works to an old weir, as the timber piles can present formidable obstacles to the driving of steel sheet piles.

Excavations in river beds are inherently unstable due to the nature of the bed material and the presence of water. Major works in rivers will almost certainly require the construction of a cofferdam (using steel sheet piles or earth fill). This will need to be dewatered to allow construction of the foundations, requiring substantial pumping capacity.

14.4 MATERIALS

14.4.1 Introduction

Historically weirs were typically constructed from timber, rough stone and masonry materials and these materials are often encountered during weir removal or refurbishment projects. Modern weirs almost invariably involve some form of concrete construction, although a large variety of materials can be used depending on the size and type of weir and the local environment.

14.4.2 Use of concrete

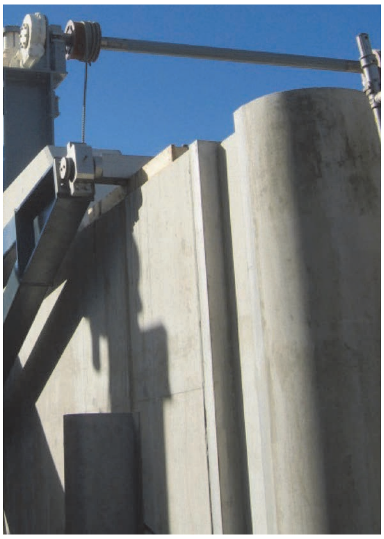
Material choice for dams, which are typically of much larger material volume than weirs, can be a matter of some discussion. For weirs, which are typically smaller, and by definition subjected to wetting across most of the structure, the choice of primary construction material is much less variable. Stone and stone-filled gabion baskets can be used for small rudimentary structures and rock ramps, sheet piles are sometimes used for simple structures, but concrete is usually selected as the primary material. This is for several reasons:

- In the UK, cement and aggregates are usually readily available at a reasonable price local to the weir site.
- Steel reinforced concrete is structurally versatile, efficient and reliable and can be placed to form watertight, monolithic structures.
- Concrete can be easily shaped into hydraulically efficient forms that are not susceptible to roughening or vegetation growth.
- Concrete can be efficiently delivered into a constrained weir site.
- Mass concrete is an efficient way of providing weight for stability that is structurally connected to the weir.
- Concrete can be made to resist weathering, abrasion and cracking.
- Once it has cured, concrete is resistant to flood damage and works can be relatively easily recovered following a flood.
- A wide variety of final appearances can be achieved through different finishing techniques.

14.4.3 Other materials

Large concrete structures can be considered unattractive and in some settings highly inappropriate. The visual impact of concrete and steel may be softened by using coping stone more appropriate to the surrounding setting. For instance block-stones may be keyed in to hide underlying concrete or gabion baskets. In an urban environment it may be appropriate to use vernacular bricks or local stone to disguise an underlying structure of concrete or steel sheet piling. It should be remembered that much of a weir's structure remains hidden from view (below ground or below water), so the use of more visually appropriate materials above water level may not add greatly to the cost. However, care should be taken not to over-mitigate, or to cause partial loss of the function of the weir by using inappropriate materials. Complete cladding of a large concrete weir can be a costly undertaking and if done inappropriately may result in a significant maintenance legacy. Arriving at the best solution will be a question of striking the right balance between potentially conflicting requirements (see **Table 14.3**).

Table 14.3 Materials typically used for weirs

Material	**Details**	**Example**
Concrete	This is probably the most commonly-used material for weir construction in the UK, due to its durability and relatively low cost. Weir structures might be constructed using mass concrete, reinforced concrete (cast *in situ*), or in some cases using precast concrete elements designed for manufacture and assembly on site. The aesthetics of weir structures have been given more attention in recent years and concrete is often considered unattractive, particularly for those structures with large walls above the water-line. Architectural techniques such as stone cladding, high levels of cement replacement, coloured concrete and textured formwork have been used in the past to try to achieve more appropriate visual appearance. However guidance and experience in the use of these techniques for river weirs is in its infancy. Non-weir specific guidance for these techniques is available (eg Concrete Society, 2013). In the specification of these techniques, the designer should note that weathering and algal growth in rivers can be significant and will tend to mask subtleties over time. It can be difficult to distinguish between a concrete and masonry structure in the river after a few years, regardless of what finish is specified. Indeed, textured concrete with rough horizontal ledges was deliberately chosen for the walls of Heathrow Terminal 5 Twin Rivers diversion with the aim of providing a micro-habitat for algae to grow. Non-weir specific guidance for concrete repair can be found in the BS EN 1504 series.	
Steel sheet piles	These are driven piles that interlock to form a notionally impermeable wall. Sheet piles are often a component of modern weirs and are used to form seepage cut-offs, river-bank walls and temporary works. In most cases they are hidden from view under the water or ground, however they can be unattractive where visible. Concrete or timber capping beams are commonly used to conceal and improve the visual appearance of the pile tops. Guidance on the design of sheet pile elements for weirs and cofferdams can be found in ArcelorMittal (2008). For weir projects it is usual practice to specify clutch sealant and/or to weld alternate piles before driving to reduce leakage through the pile clutches, which can be significant.	
Masonry cladding	Masonry weirs were commonly used in the early days of weir construction. They can be very attractive, but may exhibit loss of mortar leading to seepage through the structure. For modern structures, masonry is more commonly used for aesthetic purposes. The photograph shows concrete walls were required to resist hydraulic loads, however, the weir repairs were conducted in the same style as the original construction, using stone masonry reclaimed on site to clad the walls.	

Material	Details	Example
Brick	For small structures in an urban setting, the right choice of brick cladding can create an attractive weir. Engineering bricks should be selected where durability and frost resistance is required. The photograph shows where a concrete weir has been clad in reclaimed bricks above the water-line. Where bricks are used in the water, issues can be found with long-term durability, including loss of mortar and frost damage.	
Steel hydraulic gates	Small hydraulic gates may be constructed from steel, timber, HDPE, cast iron or other materials. Larger gates tend to be made of steel. Gates are fabricated in a controlled environment off site before being blast cleaned and painted. Smaller gates can be galvanised, however, it is more common to use a modern paint system as this avoids issues with heat distortion of the steel. Refurbishment of existing steel gates can in some cases be comparable in cost to fabricating new gates. This is because the gate must either be removed to a workshop, with all of the access and temporary works that this entails, or controlled conditions for preparation and painting must be established on the weir.	
Rock	Relatively large rocks of similar dimension have been used to form the weir structure, with concrete infill to ensure a suitable depth of flow is maintained over the weir for fish passage. Graded 'rip-rap' rock is also commonly used as scour protection downstream of weirs. Angular rock is usually preferred and a mixture of rock sizes ensures that the interstitial voids between large rocks are filled and that the material interlocks to resist movement. As well as being large enough to avoid being washed away, the rock must be hard, homogenous and sufficiently durable to resist weathering in the river. For a comprehensive guide to the use of rock in hydraulic engineering, see CIRIA, CUR, CETMEF (2007). This rock ramp weir was installed to improve salmon migration.	

Material	Details	Example
Gabion structures	Can be a cheaper alternative to concrete or masonry equivalents, with a more natural appearance when colonised by vegetation. Inherent permeability can aid drainage through retaining walls. Gabions can be used in box form for retaining walls or Reno mattress form for erosion protection. Gabions need to be properly constructed with due attention paid to filling the baskets, limiting or preventing seepage with membranes, and durability of the wires. Corrosion rates can be unacceptably high in acidic waters and sometimes plastic coated wires are specified to reduce corrosion. Design guidance can be found in Charman *et al* (2001) It should be noted that the use of gabion baskets in weirs is not supported by SEPA due to the risk of entrapment to fish and canoeists (SEPA, 2015b). Where gabions are used, it is common practice to brush friable topsoil into the finished baskets, to promote self-vegetation. Here gabion weirs have been used to form a fish pass at Kidlington on the River Cherwell.	  Courtesy Darryl Clifton-Dey
Timber	Historically timber was an important material for weir construction and was used for timber piles, beams and shuttering that could make up a large part of a weir. For modern weirs, timber can be used to hide unsightly features of modern weirs and are commonly used in the construction of attractive handrailing and decking for publicly accessible weirs. Guidance on the use of timber in river engineering, including sustainable procurement, is given by Crossman (2004). This paddle and rymer weir on the River Thames uses timber posts and boards to retain a head of water.	

14.5 STRUCTURES

14.5.1 Introduction

The superstructure of a weir is built onto the foundation structure and might include elements such as:

- A bridge or walkway, to allow pedestrian or vehicle access over the weir and access for operation and maintenance.
- Piers, to guide flow and support gates on the weir crest, or to support a walkway.
- Wing walls, to guide flow and prevent circumnavigation of the weir, or to support a walkway.
- Hydraulic gates, to control water flow over the weir, including arrangements to connect the hydraulic gates to the weir.

The design of the civil works for a weir superstructure above the foundation does not differ dramatically from the design of conventional building structures. However, the structures will be subjected to hydraulic loading (**Table 14.1**) and exposure due to being located in the river environment. Structural design of concrete, masonry, steel and timber structures is broadly covered in the relevant standards within the Eurocode suite, BS EN 1990 to BS EN 1999. Hydraulic gate design is covered separately by various international standards. This section of the guide does not provide supplementary structural design guidance, but is intended to highlight how weir-specific issues might be considered within this framework.

Other design issues that need to be considered include:

- operating equipment, eg gate hoists, gearboxes, actuators and power supply
- electrical, instrumentation, control and automation.

14.5.2 Walkway

Weirs are commonly used as crossing points over the river. If access is required over a weir, either to operate the weir or to allow an access route over the river, a weir bridge or walkway will be required. These will be in use every day so should be carefully designed to provide ergonomic operation and to ensure the safety of operatives and other people who may be on the weir. Walkways are also usually the most visible part of the weir structure and aesthetic design is very important. For prominent weir structures it may be necessary to consult an architect to develop a visually appealing or at least visually congruous walkway structure. Structural design of public footbridges is covered in BS EN 1990:2002 and BS EN 1991-1-7:2006+A1:2014 and the associated national annex.

A degree of judgement and a suitable risk assessment is required in the specification of fencing and edge protection. It is not usually necessary or desirable to provide edge protection to large reaches of the river-bank, but areas local to the weir where falls from height are a risk, or where hydraulic conditions are hazardous, should be provided with handrails and toe boards. A balance should be struck between preventing unauthorised access or accidental falls and hindering access to affect a rescue if required (see **Section 10.3**).

Weir walkways accessible to the public need special consideration to cater for particular users. Closed-spaced low-level railings are required to protect children from falling through and non-slip mesh flooring should be specified with sufficiently small grid sizes to avoid injury to dogs.

Walking surfaces and steps should be well drained and provided with non-slip surfaces. Walkway decking should be fixed with captive fixings that can be removed from the top of the walkway.

Routine maintenance tasks should be considered and the designer should enable these to be carried out from a position of safety. For instance, access to ducting should be arranged so that it can be safely worked on from the weir without the need for scaffolding or dewatering.

Periodic maintenance and future overhaul should be considered and the designer should ensure that all major components are afforded reasonable access within the constraints of the site layout.

An assessment of the operational tasks required at a weir site should be undertaken. Where activities are necessary during periods of low light it would be usual to consider task lighting (see **Figure 14.7**). At unpowered sites, in-built task lighting may not be an economic proposal. In this case portable lighting must be provided if operatives are expected to work during times of low light. Safe access to and from the weir should be provided for operatives, considering that the weir may need to be operated during the night or in poor weather conditions. The gradient and width of approach ramps also need to be considered, particularly if disabled access is required over the weir. Safe entry, egress and access for sub-aqua diving to the head and tail of the weir should be provided.

This downward facing task lighting has been designed so it can be retrieved onto the walkway for changing the bulbs without endangering the operative.

Non-slip, free-draining and lightweight walkway panels can be removed without access below or losing fixtures into the river.

Galvanised tube and ball handrailing has been provided with a toe-board to prevent the loss of tools into the water.

Figure 14.7 Design for operation and maintenance

14.5.3 Piers

Piers are used to support hydraulic gates on the weir crest and to transfer gate loading to the weir foundations. They also provide a means of supporting walkways over the weir and of isolating and dewatering individual sections of the weir for maintenance.

Piers delineate gate bays to allow discrete flow discharges through separate gates or weirs. Flow patterns can then be managed across the river, for example to distribute flows to reduce scour, to manage velocities for river navigation, to deliberately scour an area in front of an intake or to provide favourable conditions for fish passage.

For weirs that are not orthogonal to the general direction of the river, piers provide a means of guiding flow in this direction over the weir crest, preventing the development of cross flows and other unfavourable hydraulic conditions.

Pier geometry is determined by a number of considerations:

- Piers will usually have hydraulically profiled noses and tails in order to minimise flow separation and reduce hydraulic contraction at the pier nose. Example of pier nose shapes can be found in the USBR (1976) and USACE (2005) design guidance. Wing walls should gradually transition to and from the weir to minimise turbulent flow.
- Piers should be made wide enough to accommodate arrangements to fix hydraulic gates (holding down arrangements) and to transfer hydraulic loads from the gate to the structure
- Piers may need recesses to accommodate embedded parts that are installed after the main concrete construction. These might include slots, niches, tracks, sills and side plates that the gates bear upon or seal against. These are adjusted during gate installation to precise positions, before being grouted in place
- Hydraulic gates should be able to be isolated for periodic replacement of seals and other gate furniture. This is usually achieved by providing facilities for upstream and downstream stop logs. Traditionally, stop logs were steel or wooden beams placed horizontally, one upon the other to form a bulkhead gate at either end of the gate bay. Today, many are fabricated from composite materials, eg coplastix. They are supported at either end in grooves formed in the pier walls. The design of the stop logs depends on the head of water that is to be retained, the gate bay span and the handling facilities available for installation and removal.
- Stop logs might be stored at a location alongside the weir, or alternatively, stored off site for delivery when required. In many cases it is useful to add a plastic sheet over the upstream face once they are in place, as leakage often occurs in the grooves and at the base. A rebate in the invert is not ideal, as this can become full of debris and difficult to clean out underwater before stop log installation. A slightly (eg 50 mm) raised rib is preferable.
- Piers may need to be sized for operational activities, for example, safe maintenance access or lifting operations.

14.5.4 Wing walls

Wing walls are the element of a weir structure that tie the weir into the surrounding river-bank and allow the geometrical transition from the shape of the river-bank to the shape of the weir side walls. Several competing requirements need to be considered during their design.

- Wing walls are engineered to ensure that flood flows continue to be directed over the weir, until the river flows out of channel at some point upstream away from the weir. This reduces the risk of damage to the weir structure, which can be caused by flows prematurely bypassing the structure and scouring out the river-bank local to the weir structure. They also promote a smooth flow transition from river-bank to the weir and back, which reduces the potential for scour near to the weir. Some examples are given in **Figure 14.8**.
- The visual appearance of river training works, wing walls and abutments needs to be considered against the need to confine flows over the weir under a variety of conditions. Wing walls are often the most visible element of the structure. Large flat concrete walls can be unattractive in some locations. For some sites it may be appropriate to reduce the size of the walls to lessen their visual impact. At other sites a composite wall might be considered (eg a low-level retaining wall with an armoured slope). Where this is not possible other options such as the use of cladding and architectural concrete techniques can be considered or, for very small weirs, softer bank protection may be considered.
- High wingwalls downstream of the weir can prevent exit from the channel of persons trapped in the weir hydraulic jump. The hydraulic jump should be designed with flushing points, however it is also important that low-level access to and from the weir pool is provided with wing walls where entrapment is a risk (see also **Chapter 10**). Walls downstream of the weir can often be made significantly lower than those upstream.

The wingwalls at this site are at a lower elevation than the road bridge upstream (the bridge is presumably designed to the bankfull flow level). So the structure is prematurely bypassed during a flood and will suffer scour damage local to the weir (shown at the same site).

This site where the walls have been designed at an appropriate height and flow is not able to circumvent the weir. Note the provision of safe access to the downstream of the weir.

This low weir was constructed for environmental enhancement. It has a modest drop so as not to obstruct fish movement, an uneven crest to create interest, and dumped rock on the banks downstream to resist erosion. However, the designer has neglected to confine the river upstream, and there is a risk of the weir being bypassed on the far bank. Construction of a low stone wall would easily solve this problem.

In some cases the requirement for highly visible wing walls can be avoided.

This low weir ties into a rock outcrop on the left bank. On the right bank the upstream channel is confined by a low stone wing wall. The main body of flow passes through a lower section in the centre of the weir.

Figure 14.8 Sizing of wingwalls

Piers and wingwalls are usually designed as conventional retaining walls. As well as normal load cases, the designer should consider loading that results from dewatering a gate bay for maintenance.

A common area of design complexity is the transition of the water loads from the gates into the weir structure. This might be done continuously along the gate sides (slide gates), through a series of supports along the gate side (fixed wheel gate), through a pair of trunnions located on the piers (radial gate), or through a series of hinges located on the weir sill (flap gate). Special attention should be paid to the magnitude and direction of the

forces in these areas as they can be the site of significant stress concentration and complicated load interactions, particularly if more than one gate loads onto a pier. Further guidance can be found in Erbisti (2003) and Lewin (2001).

Reinforcement design for weirs can be driven by thermal crack control, particularly if reinforcement is required to thick slabs and walls. Guidance on the design of reinforcement to minimise crack width or measures to avoid the risk of cracking is given in Bamforth (2007). The level of reinforcement can be reduced if the designer considers avoiding reinforcement in concrete included for the sole reason of adding weight to the weir. A common arrangement for a weir apron slab is to design a relatively thin layer of reinforced concrete tied into an underlying mass concrete slab. Although weirs are structures that retain water, the designer should also consider whether the weir in question is a structure for the containment of liquid as intended by BS EN 1992-3:2006 or whether a small amount of leakage through the concrete structure of the weir would be tolerable. If this is the case, then the requirement for crack control might be relaxed and the general provisions in BS EN 1992-1-1:2004 (paragraph 7.3.1) adopted.

14.5.5 Hydraulic gates

In summary, the gate geometry and operational equipment are usually selected so that:

- the functional requirements of the weir are met (hydraulic capacity, retained pond level, fine flow and water level control, discharge of debris and ice, emergency closure etc)
- the gate may be lifted clear of a given flood level
- access for routine maintenance can be easily achieved
- access to replace the gates and other major equipment is possible without excessive expense.

Structural design is carried out to:

- ensure the ultimate capacity of the gate to resist the loads imposed upon it
- to provide suitable stiffness and rigidity to minimise deflection when subjected to the various load case conditions
- ensure safe load transfer to the weir foundation.

The design of hydraulic gates varies greatly from structure to structure. For more detail the reader should see Erbisti (2003) and Lewin (2001). Structural design is usually carried out to international standards, eg HGPA (1986) (Japan), ASTM C42/C42M-13 (USA) or DIN 19074-1:2014-11 (Germany).

14.5.6 Operating equipment

Gates can be operated by a variety of means including by water pressure (eg displacer operated radial gates) or by movable hoists (eg one hoist servicing multiple gates). However, usually a fixed hoist will be provided at each gate that might be a screw or spindle lift, wire rope and drum, roller chains, rack and pinion or hydraulic cylinders. Operating equipment must be selected to provide sufficient motive force to overcome the gate weight, frictional forces, hydrodynamic forces and accidental loads. The equipment should be arranged to lift the gate above a design flood level.

In selecting operational equipment, redundancy should be considered. How will the weir be operated in the absence of power? Is a back-up generator necessary? Will hand-winding be acceptable, or should portable powered actuators be provided for back-up and how will access be gained in a flood event? A hand-winding facility is usually required and in this case selection of gearing is an iterative process to minimise the time to hand-wind and the hand-wind torque while ensuring acceptable performance under electric operation.

Design should also consider the ease of access for maintenance, and where this is difficult low maintenance or maintenance-free components should be specified, for example, where bearings are not accessible, dry running marine bearings should be considered. More detailed guidance is available in Erbisti (2003) and Lewin (2001).

Designers of new machinery must carry out a machinery risk assessment in order to meet the requirements of Directive 2006/42/EC (The Machinery Directive) and The Supply of Machinery (Safety) Regulations 2008. Guidance in the preparation of machinery risk assessments can be found in ISO 12100:2010 and ISO/TR 14121-2:2012.

14.5.7 Electrical, instrumentation, control and automation

Power supply

Most gated weirs in the UK will be powered by mains electrical supply. While the sole use of internal combustion engines to power weirs is a rarity in the UK, it is common practice to make provision for power by a generator in emergency. For equipment that requires a power supply, an assessment of the existing supply should be made to determine whether sufficient capacity is available to supply the new equipment. It is not often that weir gates within a complex are operated concurrently, however if this is a requirement the power supply should be able to accommodate this. If a new power supply is required it can be a time-consuming process to arrange a connection and steps to do so should be taken at an early stage of the project.

Instrumentation

At large structures, weir instrumentation might include piezometers for monitoring pore water pressures under the weir, or provision to measure movement of the structure over time. These provisions are however rare for the size and type of structure considered in the UK. Gauging weirs may have pipework leading to a well and small hut containing instrumentation for measuring water levels and usually telemetry for remote monitoring of river flows and levels.

It is usual to provide gauge boards and, where relevant, gate position indicators so that the operator can view the upstream and downstream water levels and understand the position of the gates. Gate position indicators come in a variety of forms and complexities. In the simplest form a pointer is fixed to the gate and moves over a graduated scale. In this case, a clear line of sight should be provided from the point of gate operation to the indicator, and the designer should consider whether the indicator and gauge will be functional for all gate positions and water levels. Parallax error (caused by the position of the operator relative to the indicator and gauge) should also be considered.

Control and automation

The designer should consider where control of the gates are carried out from. Local control is most common, using manual controls located in gate control boxes next to each gate. This gives the operator good visibility of the gate being operated and allows any problems to be quickly identified and addressed. 'Dead-man' switches that stop when the switch is released, and/or emergency stop buttons should be considered to prevent unintended operation of the gate.

Where appropriate, supervisory control and data acquisition (SCADA) can provide remote monitoring and if desired, fully automated control of a weir system. Larger weirs with multiple gates may be operated from a central control room, either close to the structure or at a remote location. The Thames Barrier is an example of such a system where 10 rising sector gates are controlled both from local pier control rooms, and a main and auxiliary control room on the south and north banks of the river respectively.

If remote control is considered, care is required to ensure that the operator has full visibility of the gate operation (often through closed-circuit television, CCTV) so that they can detect any issues as they arise. For example, they may not be aware of river users near to the weir, which would be immediately apparent to a local operative.

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15 Construction

15.1 INTRODUCTION

This chapter outlines the main considerations for weir construction that should be considered at an early stage of the planning process. It is important to gain an early understanding of how the practical requirements of construction shall be met and the timing of works in the river to best manage flood risk. The requirements for temporary works and efficient use of construction plant can be significant in terms of cost considerations, which can influence the design of the permanent works. So it is usually advantageous to arrange early contractor involvement and to consider the weir design comprehensively (ie from the point of view of both the temporary and permanent works) at an early stage.

15.2 PROCUREMENT

It is important that those planning weir projects engage contractors with the experience to foresee risks that may arise and recommend measures to minimise and manage these risks. Contractual arrangements should apportion risk to those best able to manage it, and ensure that those responsible for managing individual risks are allocated commensurate resources to do so. Selection of project participants on a 'lowest cost' basis does not always allow for proper risk management and the consequences for a weir project can be severe. Instead 'value for money' criteria should be established to ensure that experience, skills, equipment, method, team-working and other quality-based metrics are measured, as well as bottom-line price. See Morris and Simm (2000) for a more detailed discussion of the procurement considerations for weir projects.

15.3 MANAGING RISK

A risk register will have been developed by the implementation team to give a broad picture of perceived risk from different perspectives. Risks that might affect the delivery of the project should be identified (in terms of quality, cost and programme, as well as ability to meet the project objectives). The document should be used as a tool to actively manage risk and should inform where resources can be directed to eliminate, reduce or mitigate risk. Those best placed to manage individual risks should be given the responsibility and resources to do so. The risk register should be updated throughout the construction period.

Table 15.1 shows a prompt list identifying key risk areas for weir construction, rehabilitation and removal projects. This list is not meant to be exhaustive.

Table 15.1 Implementation risk prompt list (after Morris and Simm, 2000)

Access	Ecology	Obstructions
Adjacent property	Electricity	Operation
Adjacent works	Experience	Programme
Angling	Explosion	Procurement
Archaeology	Fire	Rescue equipment
Bank protection	Fish	Rock
Bank stability	Floating plant	Sand
Bed material	Flood flows, levels	Scour
Boats/navigation	Flood warning	Seasonal variations
Breach	Ground conditions	Sediment
Bridge	Groundwater	Services
Buried services	Heritage	Signage

Access	Ecology	Obstructions
Canoes	Hydraulic safety	Silt
Cash flow	Hydrology	Site access
Cofferdams	Ice	Site compound
Confined spaces	Invasive species	Site drainage
Consents	Landowners	Sluices
Contamination	Landscape	Stability
Contract	Land use	Steel price
Corrosion	Livestock	Storage
Cranes	Material sourcing	Structural makeup
Currents	Noise	Survey
Debris	Piling	Swimming
Deposition	Plant	Temperature
Design	Pollution	Timber
Divers	Pontoon	Traffic management
Drainage	Public access	Vandalism
Dredging	Public relations	Water levels
Drowning	Pumps	Weather

15.4 ACCESS AND ACCOMMODATION

All construction works require access to the site to allow the movement of plant, labour and materials, and to facilitate the removal of any waste from the site. In the context of river works, sites are often difficult to access and may incur environmental impacts.

Riverine sites can be highly constrained, however sufficient area should be allowed for material storage, car parking, manoeuvring of plant and work areas (**Figure 15.1**). Where this is not possible local to the weir, a compound located some distance from the weir site may be necessary. Where possible the site compound should be located on high ground, so that that temporary offices and material storage are not affected by flooding. In urban areas vehicle access is commonly not possible due to buildings fronting the river, and also may not be acceptable due to noise, dust and traffic congestion. Access along the river bed, or by using floating plant can be an option, however these may also have associated risks and costs. The river may not be deep enough to accommodate the required plant and damage to the river bed can occur. Using the river for access means that high flow can completely stop construction progress.

In rural areas, vehicle access will often be across agricultural fields in the floodplain. Ecological surveys, land agreements and any necessary consent should be obtained in advance of the required access. If necessary, agreement should be reached with the planning authority concerning any material placed for access tracks. It can often be the case that this must be removed following completion of the works.

Access requirements should be identified early on in the project, ideally with early contractor involvement (ECI). This allows the following to occur in good time:

- negotiations with affected landowners and other interested parties
- enabling works such as vegetation clearance, tree pruning or footpath diversion
- ecological surveys carried out for the weir project can include the areas required for access
- design of temporary works including tracks, ditch crossings and service diversions.

As with all construction sites, adjacent activities should be considered during construction planning and where possible the public should be kept away from the working site with formal diversion of footpaths and clear signs. Information boards can provide a useful way of satisfying public interest without unsafe intrusion onto

the site. Movement of heavy vehicles should be planned to avoid busy periods (eg the school run) and waterborne plant movements should be carefully managed to avoid interference with other users of the river.

The timing of works to navigation weirs can be restricted by operational requirements. In the UK, cruising waterways are generally busy from Easter to October whereas works in watercourses are best undertaken during low flow conditions (typically the summer months). Commercial waterways operate continuously and works may have to be carried out in the wet and emergency works may have to be carried out during challenging flow conditions.

A large compound area located adjacent to a weir reconstruction on the River Thames. Note that Riverine sites can be highly constrained.

Figure 15.1 ***Construction compound***

15.5 RIVER DIVERSION

For new weirs or for existing weirs where continued impoundment is not required it is sometimes possible to manage the river flow directly through the site. There are also examples of weir construction without river diversion such as 'in the wet' method at Olmsted Weir on the Ohio River, where a catamaran was used to place large precast concrete weir shells (see **Websites**).

Websites
Olmsted locks and dams:
https://en.wikipedia.org/wiki/Olmsted_Locks_and_Dam

However, these are rare and it is usually necessary to divert the river to provide a dry working environment for construction of the weir.

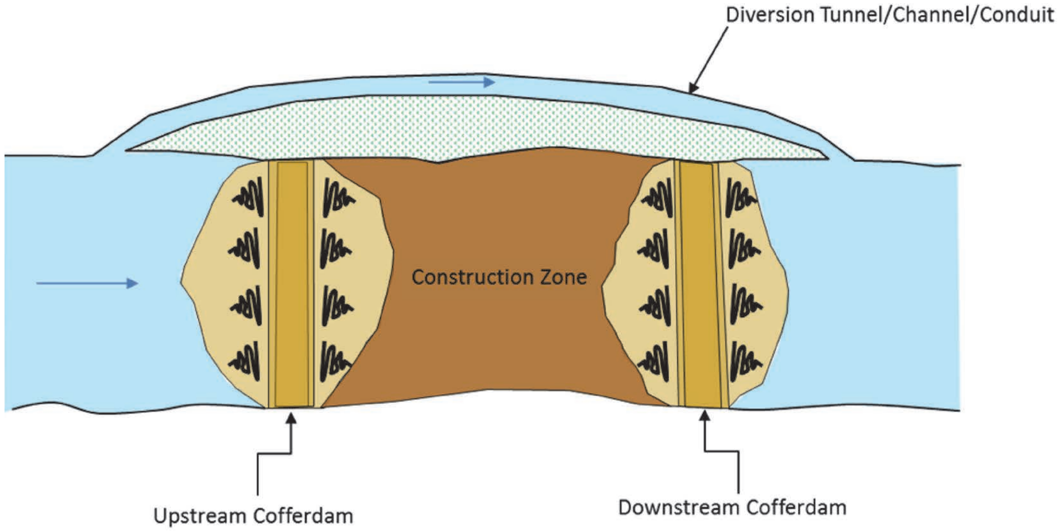
A single-stage construction involves excavation of an offline diversion channel or provision of a conduit or tunnel in order to divert the river around the whole construction zone, which enables the weir to be built in one stage (**Figure 15.2a**). In this case it is important that the river diversion is properly located and reinstated (if necessary reinforced), to prevent the river from reverting to the diversion channel during periods of high flow.

For multiple stage construction, a proportion of the channel is isolated within a cofferdam in order to construct part of the weir (**Figure 15.2b**). The remaining channel width is used to pass flow. Once the first part of the weir has been completed, it can be used to manage flows, and the remaining part of the channel can be isolated in order to complete the weir. It is common to carry out multiple stage constructions over several seasons, taking advantage of low flows and closing the site during high flows. In this case it is important to consider the temporary condition of the part-constructed weir and to ensure that appropriate scour protection is provided to protect it (and where applicable the partially removed old weir). It is also important to note how in-channel works affect upstream flood risk and whether temporary works should be removable in the event of a flood.

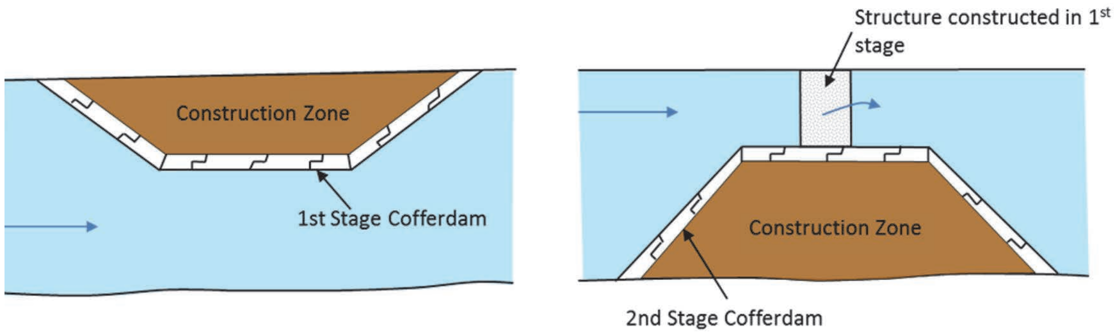
Cofferdams are temporary structures that limit the entry of water into the construction zone, at least to the degree where pumps are able to dewater the area. Cofferdams and other dewatering works should be carefully designed because they protect the workforce from the river. Also, they can be subject to differing and onerous loading at various stages of construction due to, for example, excavation within the cofferdam, demolition works, scour and flooding. Cofferdam crest levels should be carefully considered, noting the hydrological record, accepted level of risk and the hydraulic impact of temporary works in the channel. Both upstream and downstream water levels need to be assessed.

Cofferdams and dewatered areas present specific hazards to the construction workforce. So the design, construction, monitoring and maintenance of cofferdams should include a careful and detailed risk assessment addressing, among other things:

- whether the cofferdam is a 'confined space' under the Confined Spaces Regulations 1997



a Single stage construction



b Multiple stage construction

Figure 15.2 Single and multiple stage construction (after Novak, 2007)

- falls from height and slips in wet environment
- access and egress during an emergency
- health hazards from contaminated water
- hazardous gases in confined spaces
- hazards from temporary power cables in water, or existing services
- noise and vibration from piling
- contact with moving equipment and plant
- flooding caused by failure of cofferdam walls.

Before dewatering a cofferdam, it is usually prudent to check the capacity of existing structures to deal with the resulting loading. In the case of many old structures, the presence of water in the river is the only thing supporting them, and dewatering can lead to catastrophic failure. In some cases it may be necessary to strengthen existing river walls before dewatering.

A fish rescue is usually required before dewatering a cofferdam, to prevent fish being trapped when the cofferdam is closed. This is usually achieved by obtaining the necessary consents from the relevant authority and employing a specialist to repeatedly electro-fish the cofferdam to temporarily stun and move them back to the river. It is usual practice to lower the water level within the cofferdam in order to concentrate the trapped fish and increase the percentage caught. During initial dewatering pump intakes should be fitted with fine screens to prevent fish being drawn into the pumps and killed. Crayfish should also be removed when found and either released back into the river (native species) or humanely dispatched (non-native species).

For shallow cofferdams it may be appropriate to form the enclosure using large 'dumpy sacks' filled with shingle (sand should not be used as it can be washed out) and sealed on the upstream face. Small cofferdams may also be formed using clay fill. The use of inflatable water-filled temporary dams is also common up to water depths of around 2.5 m. However, for most significant weir works in the UK, cofferdams are usually formed using steel sheet piles that are either cantilevered, propped or tied to resist water forces. Sheet piles offer the following advantages:

- They can be driven to depth to cut-off seepage and mitigate against scouring.

- They are resistant to flood flows and overtopping.
- They are relatively flexible to deal with unforeseen geometries and conditions, which are common in river works.
- They can incorporate removable sections for flooding of the works. This can be useful for wet testing of equipment at the end of the construction. In some cases flood risk is managed by incorporating flood gates within the cofferdam wall, which can be opened to pass flood flows through the works.
- In many cases the temporary sheet-piling can be incorporated into the permanent works design.

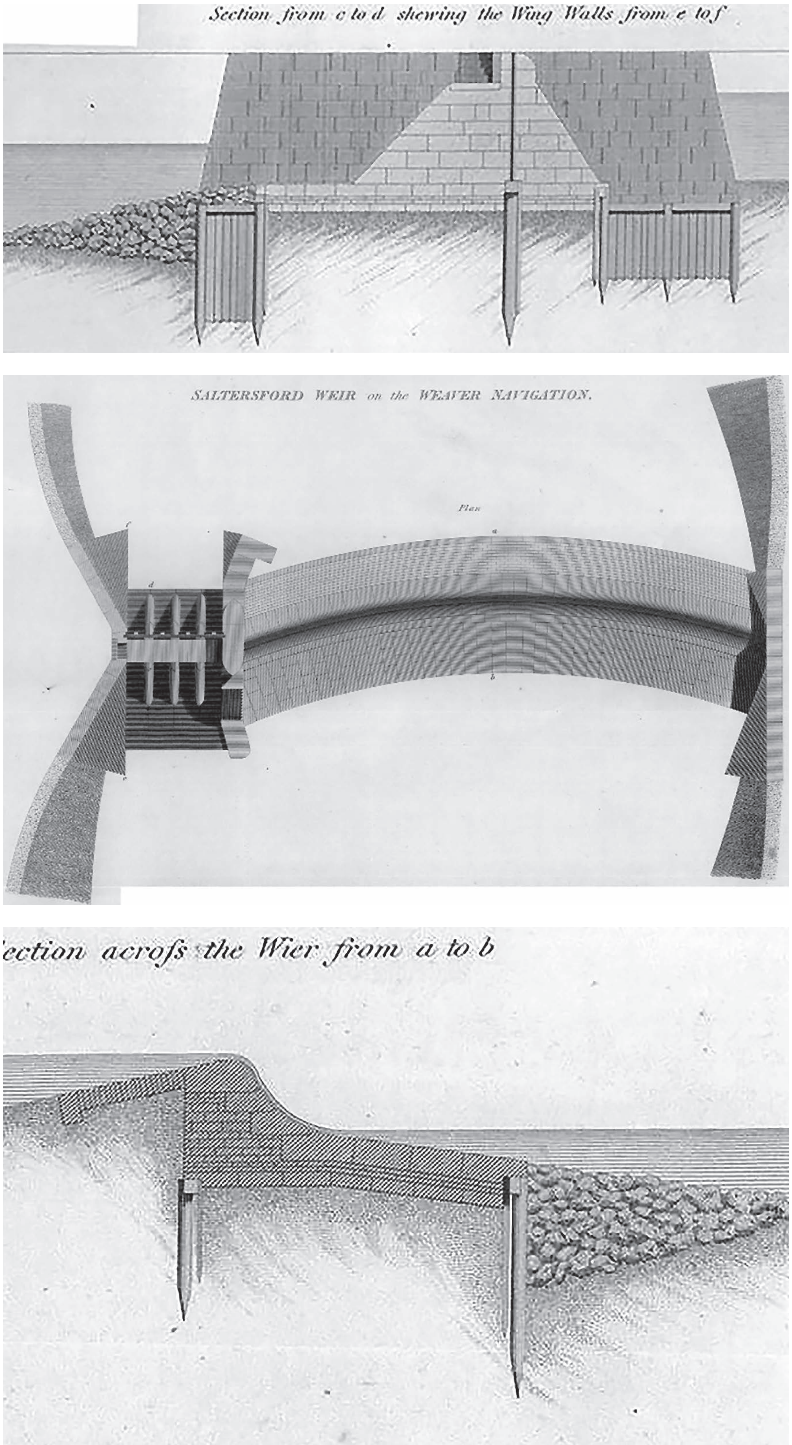


Figure 15.3 Detail of Saltesford weir on the Weaver Navigation showing timber piling supporting masonry structure (from Thomas Telford, 1838)

One half of the weir is being worked upon within a cofferdam formed by large ballast baskets. An access platform has been constructed across the remaining channel and flows are passed through culverts beneath the platform.

The stream has been diverted through a temporary fabric culvert, keeping land acquisition and environmental impact to a minimum.

This shows a bridging section that was constructed to allow demolition of the existing weir apron in relatively dry conditions. The sheet pile line was later driven through the newly cleared ground to form a watertight cofferdam.

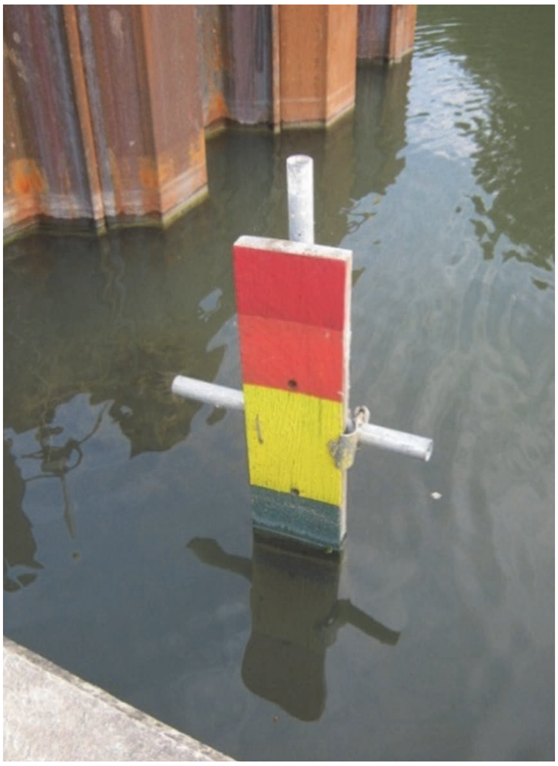
Figure 15.4 Temporary works examples

Guidance for the design and construction of sheet piled cofferdams can be found in Williams and Waite (1993).

Difficulties can be encountered with sheet piled cofferdams due to obstructions to driving. Obstructions in the ground are common around weirs, due to the presence of scour protection, old timber piles and waling beams. The contractual provision for obstruction should be considered and the risk clearly allocated (eg including a lead trench clause within the design specification). Significant difficulties are more common if sheet piles are to be driven through the line of an old weir. In many cases, removing the old structure can be more difficult than anticipated.

15.6 MANAGING CONSTRUCTION FLOOD RISK

The most significant risk to a weir project is high river flows during construction. Construction programming should take note of the risks of construction during higher flow months. The available construction window will depend upon the hydrology of the site, however, the period between the end of April and the end of October is commonly selected. The entire implementation team should be made aware of the issues around seasonal construction and how



At Radcot weir on the River Thames, the works were split over two seasons to make use of the lower flow period between April and October. A flood risk management protocol was formulated between the client, engineer and contractor during the early stages of the work. This was fully integrated into the construction contract and SMS flood warning system. The protocol involved close co-operation between the contractor and the client's operation and flood risk management staff to safely manage water levels and flows to ensure the safety of the construction workforce and to manage flood risk during the works. Water levels were used to define actions within the protocol, with green, amber and red levels resulting in various actions and communications, ranging from heightened alert, mobilisation of plant and emergency response staff, to evacuation and flooding of the works.

Figure 15.5 Construction flood risk management

delay in one area of the project can affect the positioning of the construction works in relation to the available low-flow window. The timing of project funding, financing, procurement and (in the public sector) the need to disburse annual budgets can bring programme pressures that are detrimental to construction risk management. If possible, the temptation to start a delayed project within a high-flow window should be resisted. This is one of the most common root causes of serious project difficulties.

Temporary works in the river channel can reduce the area available for flow and increase flood risk upstream. Where this is a significant issue it is good practice to prepare a construction flood risk management protocol. This should be aligned with the construction contract and where applicable the implementing agency's standard operating procedures, including being integrated into standard flood alert and flood warning communication protocols and wider emergency response plans.

The protocol should define actions to be taken at various stages of a flood, including clear contractual instructions so that inappropriate procedures do not impede timely action when it matters. Measures to manage flood risk might include:

- enhanced flood warnings to affected properties
- advance preparations to provide temporary property-based flood protection to those affected (eg sandbags)
- advance permanent property-based flood protection (in some cases this is the most cost effective measure)
- removable temporary works to allow the passage of flow through cofferdams.

15.7 REFERENCES

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NOVAK, P, MOFFAT, A I B, NALLURI, C and NARAYANAN, R (2007) *Hydraulic structures, fourth edition*, Taylor & Francis, Abingdon, Oxon (ISBN: 978-0-41538-625-8)

TELFORD, T (1838) *Atlas to the life of Thomas Telford: civil engineer, containing eighty-three copper plates, illustrative of his professional labours*, Payne and Foss, Pall Mall, UK

WILLIAMS, B and WAITE, D (1993) *The design and construction of sheet-piled cofferdams*, SP95, CIRIA, London (ISBN: 978-0-86017-361-8)
www.ciria.org

Statutes

Regulations

The Confined Spaces Regulations 1997 (No. 1713)

1

2

3

A

A1 Types of weir

A1.1 FIXED WEIRS

Key: relative merit	
	Typically good
	Typically medium
	Typically poor
	Varies

A1.1.1 Broad-crested weir

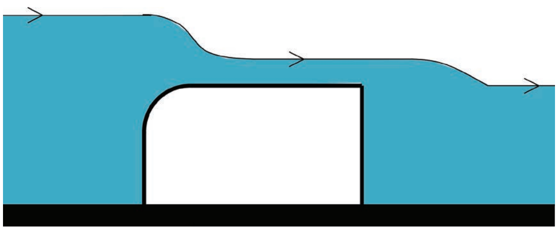

Figure A1.1 Chesterford weir gauging station on the River Cam

Description	
Broad-crested weirs comprise an overflow structure with a horizontal crest. The weir generates a localised increase in water velocity and a reduction in water level across the crest. Most weirs in rivers can be approximated to broad-crested weirs although their structure and form can vary significantly. Broad-crested weir structures can have control sections of a variety of shapes including triangular, parabolic, trapezoidal and circular. The application of a broad-crested weir for flow measurement is dependent on the weir crest height above the channel bed being sufficient to generate critical depth at a control section on the crest. Where this occurs and the length of the weir crest in the direction of flow causes the streamlines to be practically straight and parallel, a head discharge relationship can be derived (Bos, 1989).	
Uses: flow measurement	
Comparative merits	
Hydraulic efficiency	
Hydraulic safety	Depends on the downstream weir glacis and energy dissipation, a longer profile will provide safer downstream conditions
Fish passage	Velocities and flow depths over the weir will often prevent fish passage
Use for gauging	Commonly used for obtaining flow measurements. Extensive research on stage discharge relationships for this type of weir
Design complexity	Commonly used for obtaining flow measurements. Extensive research on stage discharge relationships for this type of weir. Relatively simple design process
Visual impact	Can be relatively low impact if bank structures are sensitively designed
Key references	Bos (1989)

A1.1.2 Sharp-crested weir

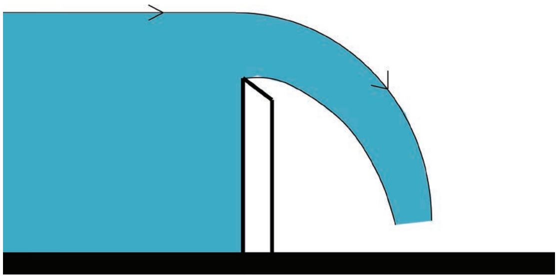

Figure A1.2 Dernford weir gauging station on the River Cam

Description	
A sharp-crested weir (or thin-plate weir) is an overflow structure where the length of crest in the direction of flow is extremely short, typically of the order of two millimetres or less. For these structures, the crest length of the weir is short enough not to influence the head-discharge relationship and the occurrence of critical flow is not relevant for discharge calculation. The behaviour of the weir is analogous to orifice flow with a free upstream water surface (Bos, 1989). ISO 1438:2008 and Bos (1989) present formulae for flow calculation at sharp-crested weirs including the derivation of coefficients required for discharge calculations. Sharp crested weirs are typically used in laboratories, small streams and in sediment free water (ISO 8368:1999), where highly accurate discharge measurements are required. As with broad-crested weirs, sharp-crested weirs can have a control section of rectangular, triangular, circular, trapezoidal shapes or other more complex forms. With a very short crest length, the nappe (the sheet of water flowing over the crest) is likely to be disconnected to the downstream face of the weir and an air pocket will form under the nappe. A sufficient supply of air should be maintained within this air pocket to prevent inconsistencies in the flow patterns across the structure. In exceptional circumstances, resonance may cause structural problems (Bos, 1989).	
Uses: laboratories or as temporary gauging structures in small streams and in sediment-free water	
Comparative merits	
Hydraulic efficiency	
Hydraulic safety	Can result in recirculating hydraulic conditions that are particularly unsafe for those in the water. These types of geometry should be avoided as standard procedure
Fish passage	Separation of the nappe from the structure makes these type of weirs particularly unfavourable to fish passage
Use for gauging	Used to obtain highly accurate flow measurements in laboratories, small streams and sediment-free water
Design complexity	Commonly used for obtaining flow measurements. Extensive research on stage discharge relationships for this type of weir
Visual impact	Can be relatively low impact if bank structures are sensitively designed
Key references	Bos (1989), ISO 1438:2008, ISO 8368:1999

A1.1.3 Crump weir

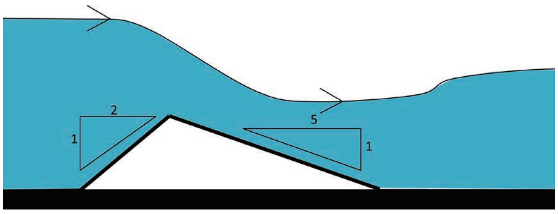

Figure A1.3 Beck Bridge weir gauging station on Lea Brook

Description	
Crump weirs have inclined upstream and downstream faces with an intersection at a horizontal crest line across the channel. The standard gradients for the structure are 1:2 on the upstream face and 1:5 on the downstream face. The principal use of the structure is for flow gauging. ISO 4360:2008 details the specific structural requirements for the installation of these types or weir and the calculation of flow.	
Uses: flow measurement	
Comparative merits	
Hydraulic efficiency	
Hydraulic safety	Generally, the shallow slope of the downstream glacis results in conditions that are relatively safer than for other geometries
Fish passage	See Rhodes and Servais (2008)
Use for gauging	Hydrometrists favour this type of weir for its accuracy and range of flow measurement
Design complexity	Well-documented design procedures and standard weir geometries
Visual impact	Can be relatively low impact if bank structures are sensitively designed
Key references	Bos (1989), Novak (2007), Rhodes and Servais (2008), ISO 4360:2008

A1.1.4 Ogee weir

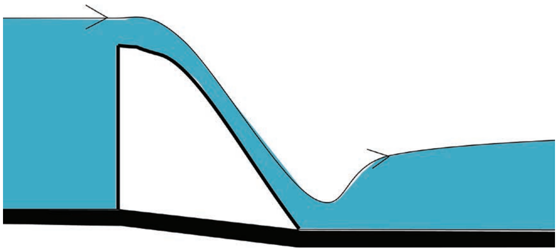

Figure A1.4 *Ogee weir*

Description The shape of the weir crest for ogee weirs is curved to match the profile of the water surface under the nappe of water flowing over the structure. This is generally recognised as being the ideal weir profile shape for the conveyance of flood water and is commonly used in reservoir spillway design	
Uses: reservoir spillways, conveyance of flood water	
Comparative merits	
Hydraulic efficiency	Hydraulically optimum weir profile
Hydraulic safety	Dependant on the downstream weir glacis and energy dissipation. A longer profile will prove more hydraulically safe
Fish passage	Velocities and flow depths over the weir will typically prevent fish passage
Use for gauging	Can be used as gauge weirs. Stage discharge relationships for ogee weirs have been studied extensively
Design complexity	Stage discharge relationships for ogee weirs have been studied extensively
Visual impact	Can be relatively low impact if bank structures are sensitively designed
Key references	USDotI (1987)

A1.1.5 Straight drop weir

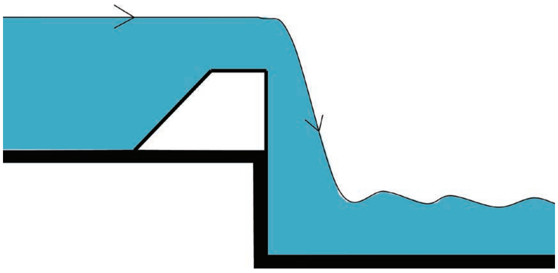

Figure A1.5 *Straight drop weir*

Description	
Straight drop weirs consist of a sharp drop after a weir crest, usually directly into a stilling basin. The steep downstream face of the weir results in plunging flow and has a tendency to create dangerous recirculation in the stilling basin. These types of weirs can be a significant safety hazard and are no longer seen as good practice for UK rivers. Existing weirs of this type can usually be altered to improve hydraulic safety	
Uses: reservoir spillways, controlling river grade, irrigation water control	
Comparative merits	
Hydraulic efficiency	
Hydraulic safety	Can result in recirculating hydraulic conditions that are particularly unsafe for those in the water. These types of geometry should be avoided as standard procedure
Fish passage	Separation of the nappe from the structure makes these type of weirs particularly unfavourable to fish passage
Use for gauging	Not typically used for gauging
Design complexity	Limited design guidance
Visual impact	Can be relatively low impact if bank structures are sensitively designed
Key references	USDA (2008)

A1.1.6 Rock weir

Figure A1.6 Lacken Weir, Ireland

Description Rock weirs and rock ramps comprise a steep reach formed from dumped or placed rock sized to withstand the flow conditions at the weir site. They may be used to create adequate head for diversion/abstraction, to maintain fish passage during low flows and to regulate channel gradient for erosion control. A rock ramp is usually provided with a low-flow channel designed to give suitable conditions for fish passage during low-flow conditions.	
Uses: maintain fish passage during low flows, create adequate head for diversion/abstraction, regulate channel gradient for erosion control	
Comparative merits	
Hydraulic efficiency	Not usually as hydraulically efficient as an engineered weir crest
Hydraulic safety	Dependent upon the ramp geometry, although usually significantly less risk of entrapment to those in the water as energy dissipation occurs gradually down the ramp and is non-uniform
Fish passage	Usually good, as long as a channel designed to give suitable conditions for fish passage during low flow conditions is provided
Use for gauging	Not typically used for gauging
Design complexity	Guidance is available, special care required to ensure low flow performance
Visual impact	Can provide a natural looking cascade of turbulent water
Key references	Acreman (2007), Armstrong *et al* (2010), SEPA (2014), Mooney (2007)

A1.1.7 Air-regulated siphon

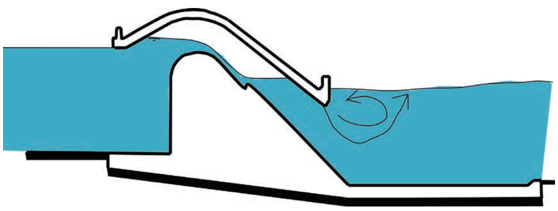

Figure A1.7 *Air-regulated siphon* (courtesty Andy Pepper, ATPEC)

Description	
Air-regulated siphons are rarely used as an alternative. These structures are self-regulating with no moving parts and are able to achieve large discharges for small increases in upstream water level. Despite these attractive features, they have rarely been constructed in the past, partly because of historic concerns around trash and ice blockages and lack of design precedents.	
Uses: water level and flow control	
Comparative merits	
Hydraulic efficiency	High unit discharge (in the right conditions comparable to a gated weir). Perceived risk of blockage by trash and ice
Hydraulic safety	Risk of entrapment in the siphon
Fish passage	Fish pass required
Use for gauging	Not typically used for flow measurement
Design complexity	Although there are a number of examples in the UK, the lack of design precedents and design guidance can deter engineers from selecting this type of structure. No moving parts
Visual impact	Visually discrete
Key references	Head (1975)

A1.1.8 Tyrolean weir and Coanda screens

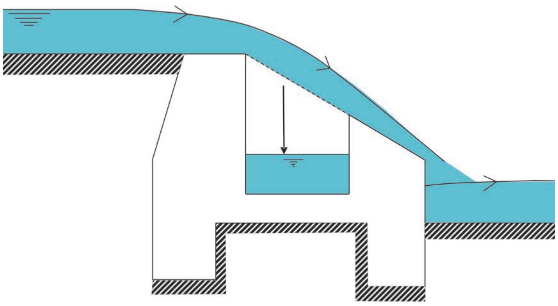

Figure A1.8 Coanda screen

Description Tyrolean and Coanda screen weirs are used for in-channel intakes on steep streams. A flat or inclined rack of bars is placed on the downstream face of the weir, to allow water to drop into an off-taking channel within the weir body. Trash and coarse sediment is excluded by the bars. Tyrolean weirs consist of bars aligned in the direction of flow that removes large material such as leaves and branches from the water surface or just below. Monitoring is required to ensure that the rack does not become clogged. Coanda screens are normally inserted on the downstream face of an ogee weir with an acceleration plate to ensure flow runs along the surface of the weir. The screen bars are orientated perpendicular to the flow direction and the spacing is tighter than that on the Tyrolean weir (with openings of 1 mm or less), as it is intended to capture fine sediment. Coanda screens are beneficial as they have no moving parts and are self-cleaning as there is a continuous flushing flow from water bypassing the Coanda screen intake.	
Uses: small channel intakes for irrigation, hydropower	
Comparative merits	
Hydraulic efficiency	
Hydraulic safety	
Fish passage	Fish pass required
Use for gauging	Not typically used for gauging
Design complexity	
Visual impact	Visual impact can be low as abstraction is directly from the channel
Key references	USBR (2003)

A1.1.9 Stepped weir

Figure A1.9 *Stepped weir (courtesy Yorkshire Hydropower Ltd)*

Description Stepped weirs are used to cascade low flows down each step causing gradual energy dissipation. These structures are used instead of vertical drop structures as the energy dissipation caused by each step reduces the size of a stilling basin if it is required. They also improve safety due to the energy dissipation and reduction of re-circulation flow at the toe of the weir. Stepped weirs are unsuitable for fish passage and so a fish pass is required.	
Uses: dam spillways, control flood releases	
Comparative merits	
Hydraulic efficiency	Typically dependent upon the weir crest shape, rather than the cascade
Hydraulic safety	Depends on the energy dissipation at the base of the cascade
Fish passage	Poor for fish passage, fish pass typically required
Use for gauging	Not typically used for gauging
Design complexity	Limited design guidance
Visual impact	Can provide a dramatic cascade of turbulent water. Good aeration as cascade generated turbulent flow at each step
Key references	Winter *et al* (2010)

A1.2 MOVABLE WEIRS

Key: relative merit	
	Typically good
	Typically medium
	Typically poor
	Varies

A1.2.1 Radial gate

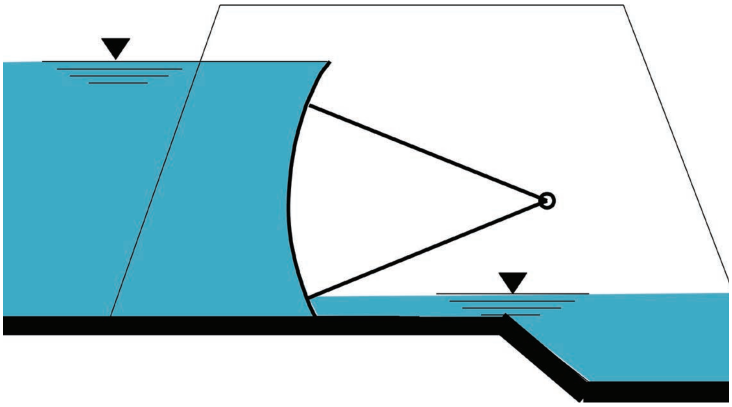

Figure A1.10 *Radial gate*

Description Radial gates consist of a segment-shaped skin-plate arranged over a supporting structure with radial arms to pass the hydraulic forces to bearings located either side of the gate.	
Uses: water level and flow control for river navigation, flood management, irrigation and abstraction, dam spillways	
Comparative merits	
Hoist capacity	Around half of the gate weight is taken by the gate pivots, which means that the lifting gear can be proportionally smaller than for a vertical lift gate, where the entire gate weight must be lifted. Gates are usually arranged so that the water force provides neither a closing nor an opening force. However, it is possible to arrange the centre of curvature of the skin-plate so that hydraulic forces assist with opening, which further reduces the requirements on the hoist capacity
Size and complexity of civil works	Piers are relatively long, concentrated loads on gate bearings
Speed/simplicity of operation	Lower lifting loads means that gate operation can be quicker for a given effort versus vertical lift gate
Flow control	For small gate openings orifice flow makes fine control difficult
Trash management	Difficult due to undershot mode of discharge
Sediment management	Good sluicing capacity
Maintenance access	Gates can be raised for inspection and minor maintenance
Design complexity	
Visual impact	Lifting gear is usually located on the gate piers above the gate. With the gates in the raised (open) position, both the gates and operating equipment are highly visible and this gate type can have a substantial visual impact, although for most cases the usual position of the gates is closed
Key references	USACE (2000)

A1.2.2 Dipping radial (or taintor) gate with compression gate arms

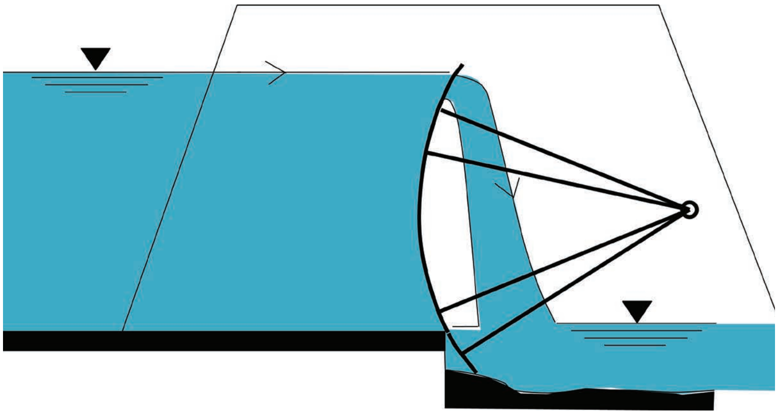

Figure A1.11 Dipping radial (taintor) gate

Description	
Radial gates consist of a segment-shaped skin-plate arranged over a supporting structure with radial arms to pass the hydraulic forces to bearings located either side of the gate.	
Uses: water level and flow for river navigation, irrigation and abstraction, dam spillways	
Comparative merits	
Hoist capacity	Around half of the gate weight is taken by the gate pivots, which means that the lifting gear can be proportionally smaller than for a vertical lift gate, where the entire gate weight must be lifted. Gates are usually arranged so that the water force provides neither a closing nor an opening force. However it is possible to arrange the centre of curvature of the skin-plate so that hydraulic forces assist with opening, which further reduces the requirements on the hoist capacity
Size and complexity of civil works	Piers are relatively long, concentrated loads on gate bearings
Speed/simplicity of operation	Lower lifting loads means that gate operation can be quicker for a given effort versus vertical lift gate
Flow control	Dipping function allows fine control of discharge rate
Trash management	Dipping function allows passage of trash over the top of the gate
Sediment management	Good sluicing capacity
Maintenance access	Gates can be raised for inspection and minor maintenance. Moving parts above water-line
Design complexity	More complex commissioning for dipping function
Visual impact	Lifting gear is usually located on the gate piers above the gate. With the gates in the raised (open) position, both the gates and operating equipment are highly visible and this gate type can have quite a substantial visual impact, although for most cases the usual position of the gates is closed
Key references	USACE (2000)

A1.2.3 Flap gate

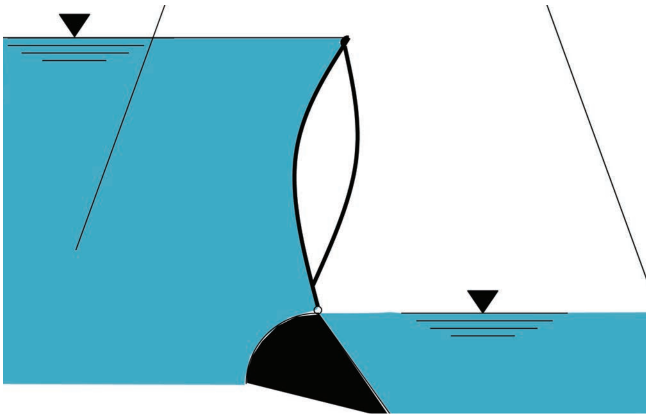

Figure A1.12 Flap gate

Description Flap gates consist of a straight or curved-shaped gate structure hinged at the base of the gate. They are typically designed to be sufficiently stiff in torsion so that they can be moved using a hydraulic actuator from one side only, for spans of up to around 20 m. This can be particularly beneficial where visual impact is of concern, as the actuating equipment may be largely hidden within one of the weir piers. Water flow is over the crest of the gate and so the discharge characteristics are good, with fine water level control and the passage of trash being possible over the top of the gate.	
Uses: water level and flow control for river navigation, flood management, irrigation and abstraction	
Comparative merits	
Hoist capacity	Relatively heavy due to the requirement to lift water force
Size and complexity of civil works	Housing for equipment in pier wall
Speed/simplicity of operation	Fast single span operation
Flow control	Good control as water is passed over the crest of the gate
Trash management	Passage over the top of the gate
Sediment management	May be issues with sediment accumulation in gate recess
Maintenance access	Bearings are underwater which can make for difficult maintenance
Design complexity	Requirement for ventilation of nappe
Visual impact	Gate hoist can be hidden in raised and lowered position
Key references	

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A1.2.4 Sector gate

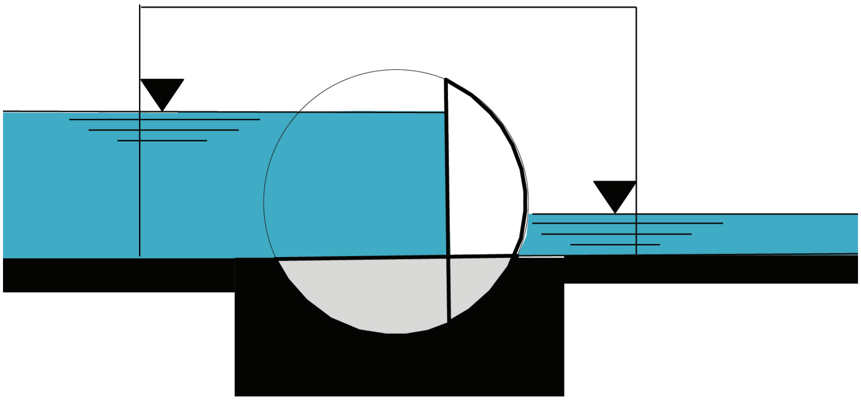
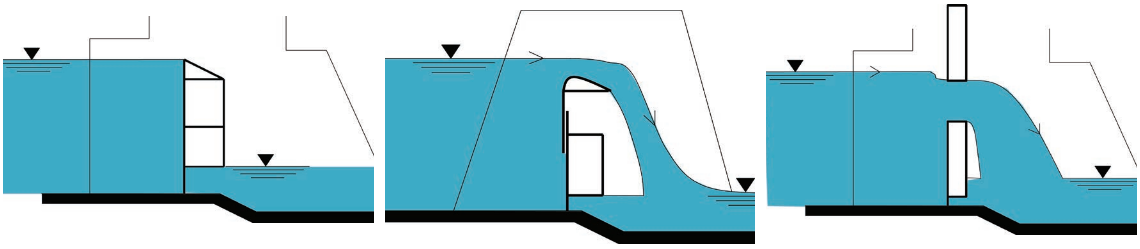


Figure A1.13 Sector gate

Description Technically a sector gate has a curved skin plate like that of a radial gate, but continued along the upper portion of the gate in the radial direction. True sector gates are actuated by water pressures on the underside of the gate. The term is commonly used to describe conventionally actuated segment gates, which are housed in the open position within a recess in the weir sill, rising upwards into a closed position. These gates are typically employed for tidal barriers where an unobstructed channel is required for navigation, as is the case at the Thames Barrier.	
Uses: tidal surge protection barriers	
Comparative merits	
Hoist capacity	High
Size and complexity of civil works	Relatively complex civil works for gate recess
Speed/simplicity of operation	
Flow control	Water flow can be both over and under the gate and so the discharge characteristics are good, with fine water level control
Trash management	Passage of trash possible over the top of the gate
Sediment management	May be issues with sediment accumulation in gate recess in rivers with high silt content
Maintenance access	Access for maintenance can be difficult
Design complexity	Relatively complex civil and mechanical design
Visual impact	Gate hidden in raised and lowered position. Large hoist equipment
Key references	

A1.2.5 Vertical lift gates



One piece gate *Hook gate* *Multiple leaf gate*

Figure A1.14 Vertical lift gates

One piece gate – description	
Vertical lift gates are the most commonly used gate for flood control in river and tidal structures. The gate leaf comprises a vertical skin plate stiffened by horizontal beams and vertical ribs. Wheels are mounted onto the edges of the gate and are located into embedded channels in the weir piers. The gates are simple in design and operation and can be operated under unbalanced head conditions and can be lifted clear of the water for maintenance. The gate is raised and lowered using lifting gear located above the gate. The lifting gear must be sized to lift the entire gate weight. Trash can become caught under the gate causing problems with gate closure and damage to the bottom seals. For this reason, modifications to this design are often considered The vertical lift gate (hook gate) is divided into two linked sections, arranged so that the upper section can be lowered, and both sections can be raised clear of the water. The vertical lift gate (multiple leaf) is divided into two or more independently actuated sections – fine water level control and trash passage is achieved by raising the upper section.	
Uses: water level and flow control for river navigation, flood management, irrigation and abstraction	
Comparative merits	
Hoist capacity	Higher than equivalent radial, may use counterweights
Size and complexity of civil works	Shorter piers than radial
Speed/simplicity of operation	Slower operation than radial, but can be operated under unbalanced head conditions
Flow control	For one piece gate with small gate openings orifice flow makes fine control difficult
Trash management	For one piece gate, trash can cause problems with gate closure
Sediment management	Reasonable sluicing capability – gate closure can be an issue
Maintenance access	Gates can be lifted clear of the water for maintenance
Design complexity	Simple design. One piece gate has many precedents
Visual impact	High visual impact due to hoist gantries
Key references	USACE (1997)

Hook gate – description The vertical lift gate is divided into two linked sections, arranged so that the upper section can be lowered, and both sections can be raised clear of the water.	
Uses: water level and flow control for river navigation, flood management, irrigation and abstraction	
Comparative merits	
Maximum gate span	Spans up to 45 m although usually significantly less for UK rivers
Maximum gate height	Gate height up to 15 m, although usually significantly less for UK rivers
Hoist capacity	Higher than equivalent radial gated weir
Size and complexity of civil works	Shorter piers than equivalent radial gated weir
Speed/simplicity of operation	Slower operation than radial, but can be operated under unbalanced head conditions
Flow control	Finer water level control is provided by lowering the top section of the gate
Trash management	Achieved by lowering the top section of the gate
Sediment management	Reasonable sluicing capability – gate closure can be an issue
Maintenance access	Gates can be lifted clear of the water for maintenance
Design complexity	Relatively simple design
Visual impact	High visual impact due to hoist gantries
Key references	

Multpiple leaf – description The vertical lift gate is divided into two or more independently actuated sections. Fine water level control and trash passage is achieved by raising the upper section.	
Uses: water level and flow control for river navigation, flood management, irrigation and abstraction	
Comparative merits	
Hoist capacity	Higher than equivalent radial gated weir
Size and complexity of civil works	Shorter piers than equivalent radial gated weir
Speed/simplicity of operation	Slower operation than radial, but can be operated under unbalanced head conditions
Flow control	Finer water level control is provided by raising the top section of the gate
Trash management	Achieved by raising the top section of the gate
Sediment management	Reasonable sluicing capability – gate closure can be an issue
Maintenance access	Gates can be lifted clear of the water for maintenance
Design complexity	Relatively simple design
Visual impact	High visual impact due to hoist gantries
Key references	

A1.2.6 Inflatable weir/rubber dam

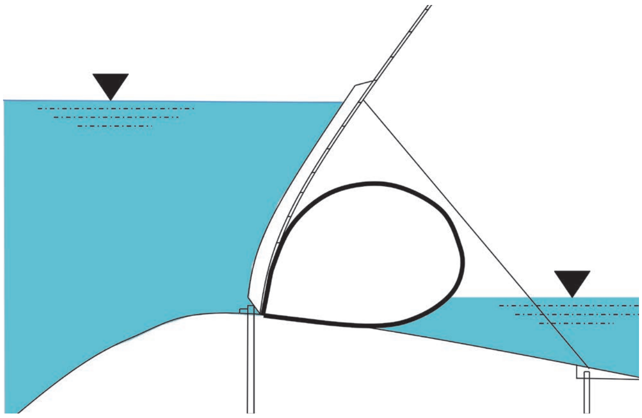


Figure A1.15 *Inflatable weir/rubber dam*

Description	
Inflatable weirs have found particular use in dam spillway modifications to increase water storage without reducing spillway capacity. However, they are also beginning to be used as weirs in the UK to retain a level of water in flood relief channels during low flows for environmental and aesthetic reasons (weir inflated), while maintaining the full capacity of the channel for flood flow (weir deflated). These structures can be used as an economic way of achieving a movable weir over a large span without visually intrusive lifting gear or gates (the actuation equipment being housed under the gate and in a small enclosure on one side of the river).	
Uses: water level control for flood management, dam spillways in particular spillway raising	
Comparative merits	
Maximum gate span	Typically economic where a movable weir is required over a large span. Spans up to ~100 m
Maximum gate height	Gate height up to 5 m
Hoist capacity	No hoisting gear. Structure can either be without gates, or with lightweight protective gate on the upstream side of the rubber dam
Size and complexity of civil works	Relatively simple civil works, supply pipes are typically embedded into the civil structure. Structure is typically lighter, with less onerous foundation requirements
Speed/simplicity of operation	Fast gate opening across broad channels
Flow control	Relatively fine water level control can be achieved. This type of gate also reduces the requirement for piers, which makes the full channel available to pass flows
Trash management	Passage of trash over the top of the lowered weir
Sediment management	Passage of sediment over the top of the lowered weir
Maintenance access	Moving parts can be below water-line
Design complexity	Relatively simple design
Visual impact	Actuation equipment is housed under the gate and in a small enclosure on one side of the river
Key references	

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A1.2.7 Sliding gate (penstock)

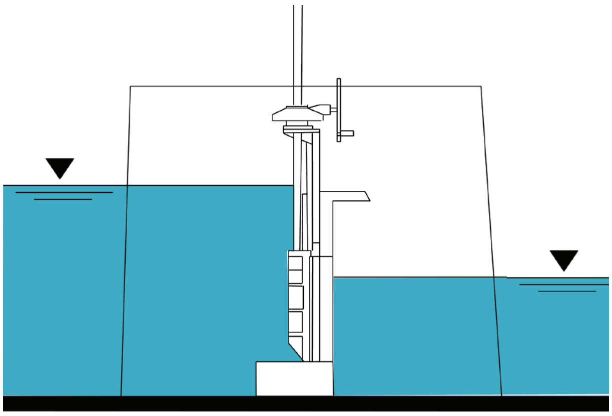

Figure A1.16 Sliding gate (penstock)

Description	
Due to their simplicity of design, construction, operation and maintenance, small sliding gates (or penstocks) are commonly found on UK weirs and sluices. The gates can be made of a variety of materials including timber, steel, HDPE and cast iron. The gate leaf slides within guides embedded in the structure. In the absence of wheels, frictional forces can be high and the gates do not usually close under gravity. Typically they are driven by electric valve actuators via spindles. Spindles can be rising (attached to the gate) or non-rising.	
Uses: water level control for flood management, drainage, abstraction and irrigation (as well as process applications such as water treatment)	
Comparative merits	
Size and complexity of civil works	Shorter piers than the equivalent radial gated weir
Speed/simplicity of operation	Slower operation than radial but can be operated under unbalanced head conditions
Flow control	For small gate openings orifice flow makes fine control difficult
Trash management	Trash can cause problems with gate closure
Sediment management	Reasonable sluicing capability – gate closure can be an issue
Maintenance access	Gates can be lifted clear of the water for maintenance
Design complexity	Simple design with many precedents
Visual impact	Can have high visual impact due to rising spindles. Non rising spindles are an option
Key references	

A1.2.8 Historic timber weirs

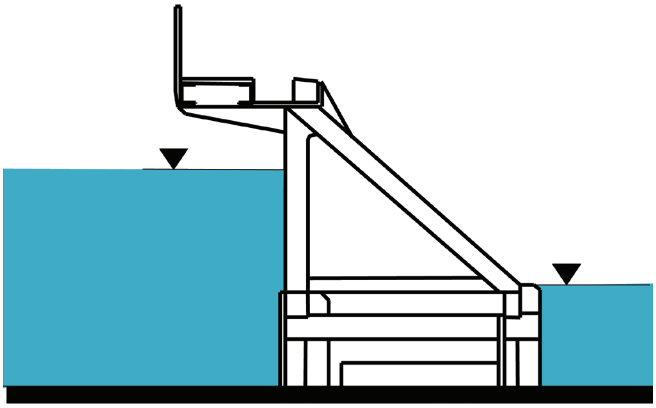

Figure A1.17 Historic timber weirs

Description	
There are a number of historic timber weir systems that are still in operation in the UK and Europe. The systems vary, but are based around the manual insertion of timber apparatus into the river. A 'needle dam' of timber rods regulates the Reuss River and maintains the level of Lake Lucerne in Switzerland. Several other examples are still used on the Meuse River. In the UK several paddle and rymer weirs still exist on the River Thames and are the remnants of flash locks, used for early river navigation. Their use is now widely being phased out due to concerns around the level of manual handling required for operation, however some examples remain to preserve the heritage value of this type of operation.	
Uses: water level control for flood management, dam spillways in particular spillway raising	
Comparative merits	
Hoist capacity	Equipment is usually placed by hand and limited to the size of apparatus that can be reasonably handled. Manual handling required for operation can be excessive
Size and complexity of civil works	Rudimentary weir slab and supporting structure
Speed/simplicity of operation	Slow and labour intensive operation
Flow control	Large gates movements are slow and labour intensive operations, however fine water level control is readily achievable when flows are low
Trash management	Small items of trash can be easily passed over the weir, larger items require labour intensive gate movements
Sediment management	Sediment can be sluiced
Maintenance access	Apparatus can be removed for inspection. Civil works are difficult to inspect
Design complexity	Relatively simple, agricultural engineering
Visual impact	Low
Key references	

A1.3 REFERENCES

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Statutes

International Standards

ISO 1438:2008 *Hydrometry. Open channel flow measurement using thin-plate weirs*

ISO 4360:2008 *Hydrometry. Open channel flow measurement using triangular profile weirs*

ISO 8368:1999 *Hydrometric determinations. Flow measurements in open channels using structures – Guidelines for selection of structure*

A2 Planning and design checklist

A2.1 GENERAL CONSIDERATIONS

What are the objectives?	
Identify functions of weir	
Ensure that the objectives for the weir, river, catchment and/or surrounding land are clear	
Information gathering	
Establish land ownership	
Gather flows and level data	
Topographic survey of the site and environs	
Environmental baseline survey	
River corridor survey	
Ground/structural investigation	
Consultation with fisheries officer	
Historic/archaeological survey	
Investigate access routes for construction	
Consultation	
Identify all stakeholders and interested parties	
Are there any navigation rights?	
Is river used for recreation (canoeing, angling etc)?	
Are any rights of way affected?	
Is land drainage or flood defence consent required?	
Are there any protected sites (SSSI, SAC, AONB)?	
Is planning permission needed?	
What are the options?	
Is a weir necessary?	
Have alternatives to a weir been considered?	
Is there an opportunity to improve the weir for sediment transport, fish, canoeists, safety, amenity, and/or the environment?	
Have all of the potential impacts of removal been assessed?	

A2.2 DESIGN ISSUES

Hydraulic design	
Flow range in river. Design maximum flow	
Impact on water levels throughout flow range	
Impact on flood risk	
Check that hydraulic jump is always in stilling basin	
Check hydraulic hazard and the need for mitigation	
Safety issues	
Public safety	
Safety of land and water users	
CDM 2015	
Operation and maintenance activities	
Need for warning signs, fencing, life-saving equipment	
Safety during construction	
Structure	
Need for cut-offs to reduce seepage	
Design to prevent bypassing in floods	
Check substructure for uplift	
Need for erosion protection on bed and banks	
Stability and durability in flood flows	
Choice of appropriate fish pass	
Hydrometric (flow monitoring) weirs	
Suitable approach flow conditions	
Sufficient head across weir in all flow conditions	
Choice of appropriate weir type	
Sediment/weed growth problems	
Opportunities	
Improvements to local habitat	
Remove barriers to fish migration or sediment transport	
Improved conditions for wildlife	
Improved conditions for canoeists	
Opportunities for hydropower generation	
Opportunities for recreation and amenity	

A2.3 ENVIRONMENTAL ISSUES

Potential impacts	
Disruption/loss of fish migration and spawning	
Damage to local landscape	
Effect on local groundwater regime	
Loss of historic/heritage value	
Local wildlife (otters, birds, invertebrates)	
Loss of amenity and recreation value	
Local residents (noise, view, access rights, etc)	
Land acquisition issues	
Environmental design	
Landscape design	
Appropriate materials/finish/colour	
Potential to improve habitat variety	
Current/future water quality constraints	
Appearance in low flow conditions	
Geomorphological issues	
Sediment continuity along watercourse	
Sedimentation upstream of new weir	
Scour of upstream sediment (removal or lowering)	
Scour downstream of a new weir	
Erosion in response to weir removal	
Mitigation measures	
Construction issues	
Pollution control during construction	
Timing to minimise impact (fish, birds, river users)	
Temporary diversion of footpaths	
Need for fish rescue	
General disturbance to established habitats	
Noise during construction	
Access for construction	
Risk of damage/disruption in flood flows	
Temporary works (eg flow diversion)	
Public safety/information (fencing, signboards etc)	

A2.4 OPERATIONAL ISSUES

Safety of operation and maintenance staff	
Need for lighting at the weir site	
Assessment of likely debris load	
Facilities for debris storage and/or removal	
Safe access to all parts of the structure	
Site security, fencing and walkways	
Need for periodic removal of sediment	
Operating plan when weir or equipment fails	
Provision for dewatering (eg stop log grooves)	
Maintenance plan and schedule	
Maintenance equipment needs	

A2.5 DECOMMISSIONING

Has ownership of the weir been confirmed?	
Is refurbishment an option?	
Check full range of impacts	
Release of contaminated sediments	
Impact on water levels and groundwater	
Exposure of archaeological finds	
Historic or heritage loss if removed	
Impact on navigation and amenity use	
Impact of river ecology	
Impact on river geomorphology	
Impact on upstream infrastructure	

A3 Case studies

A3.1 INTRODUCTION

This appendix gives case studies covering the full range of weir options from failure or removal of a weir, to modification and construction of new or replacement weirs. The case studies have been provided by authors, members of the PSG and from Rickard *et al* (2003). **Table A3.1** summarises the case studies and the source.

Table A3.1 List of case studies

Ref	Name	Description	Source
A3.2	River Browney, Co. Durham	Failure of former mill weir and study of geomorphological adjustments	Duncan Wishart, Environment Agency
A3.3	Wooler Water, Northumberland	Lessons learned from failure of channel stabilisation scheme	Duncan Wishart, Environment Agency
A3.4	Kirkham, North Yorkshire	Trial water level lowering and study of river responses before modifying weir and sluices	Duncan Wishart, Environment Agency
A3.5	Afon Aran, Gwynedd	Removal of weir in environmentally sensitive urban area as part of wider flood risk management scheme	Oliver Lowe, NRW and Joanne Barlow, Black & Veatch
A3.6	River Irwell, Manchester	Removal of numerous weirs to improve river status under the WFD	Seb Bentley, JBA Consulting
A3.7	River Wandle, Greater London	Removal and lowering of weirs from a heavily modified waterbody to restore good ecological potential	Tim Longstaff, SE Rivers Trust
A3.8	Buxted Park, East Sussex	Removal of weir to restore fish passage and natural processes	Fola Ogunyoye, Royal HaskoningDHV
A3.9	Pledge's Mill, Kent	Lowering of mill weir to restore fish passage and more natural flow conditions, while protecting buildings and infrastructure	Rob Gauldie, Mott MacDonald Ltd
A3.10	Weir X, Gwynedd	Improving safety at a flow measurement weir	NRW, JBA, EPD
A3.11	Sharpsbridge, East Sussex	Construction of rock ramp to improve fish passage	Fola Ogunyoye, Royal HaskoningDHV
A3.12	Rushey weir, Oxfordshire	Replacement for historic paddle and rymer weir, from options appraisal to construction	Environment Agency/ Mott MacDonald Ltd
A3.13	Dog Head Stakes, Berkshire	Replacement steel sheet pile weir with fish bypass to maintain navigation	Richard Leigh, Canal & River Trust
A3.14	Green Street weir, Speyside	Modification of weir to create a deeper channel for fish passage	Fola Ogunyoye, RHDHV
A3.15	Hoo Mill, Staffordshire	Installation of rock chute downstream of a bridge invert to restore fish passage	Environment Agency
A3.16	Former mill weir, northern England	Repair and replacement of a weir following two breaches to protect infrastructure from undermining	Environment Agency
A3.17	Little Bollington, Cheshire	Improvement of historic mill weir in sensitive area for flow gauging	Environment Agency
A3.18	Northenden weir, Manchester	Rehabilitation of former mill weir to repair damage to apron and restore fish passage	Environment Agency

A3.2 RIVER BROWNEY, CO. DURHAM

A3.2.1 Introduction

Wall Nook weir on the River Browney is located near the village of Langlee Park, 6.5 km north-west of Durham city centre. The weir was constructed in the 1600s to supply water to a flour mill 100 m downstream. It was thought to have been re-constructed, with a brick crest and stone face covering an internal structure of wooden piling and stone. In September 2012, the weir collapsed during a large flood event, with a breach of about one-third of the length of the weir (**Figure A3.1**).

A3.2.2 Immediate impacts

The collapse triggered a series of rapid morphological adjustments as the failure progressed during the flood event. These involved rapid acceleration of flow in the near-bed zone, bed mobilisation leading to a step (knick-point) migration and bed lowering upstream, bank collapse due to bed lowering and flow acceleration, and sediment release downstream. These factors were recorded within a fortnight of the collapse, but were likely to have occurred relatively quickly during the flood event following collapse of the weir.

The river ceased to be impounded by the weir and as a result water levels upstream fell significantly, flow velocities increased and variations in flow depth and velocity (spatially and temporally) increased. The drop in water level extended 550 m upstream with a maximum water level drop at the weir of about two metres. The former water level was clearly visible in the river-banks as an abrupt loss of vegetation cover. The section of valley side, extending up to 100 m upstream of the weir, showed no evidence of failure (**Figure A3.2**). Here the material properties of the river-bank (stiff glacial till) resisted erosion and remained geotechnically stable. Despite some minor shoreline erosion, stemming from past flow impoundment, the slope of the valley side was the same below the water-line as that above (**Figure A3.2**).

On collapse of the weir, a knick-point in the long-profile of the bed formed at the breach, generating high-flow velocities, which mobilised material that had previously been deposited in slow-flowing water upstream of the weir, leading to erosion. The knick-point then migrated upstream, gradually declining in slope until the reduced slope of the knick-point and falling river levels combined to lower flow energy at the bed, causing it to stop about 290 m upstream of the weir. The knick-point took the form of a steep riffle-like feature and could best be described as a 'knick zone' (**Figure A3.3**). As it migrated upstream, the sediment released was stored in the channel downstream, partly compensating for the initial bed lowering. Knick-point migration resulted in a net bed incision averaging about 300 mm.

The reduced water levels, increased flow velocities and bed lowering combined to trigger a number of bank collapses. These were all recorded downstream of the knick-point, indicating that bed lowering was an important contributing factor (**Figure A3.3**).

Figure A3.1 Wall Nook weir before (a) and after (b) failure

This indentation in the river-bank was the result of shoreline erosion before failure created and clearly indicates the drop in water level 100 m upstream of the weir. There was no evidence of failure here.

Figure A3.2   Drop in water level upstream of the weir

Figure A3.3   'Knick zone' and bank erosion between the knick zone and weir

Bank collapses were localised and restricted to individual mass collapses of floodplain sediments rather than long continuous lengths of collapse.

The localised nature of bank collapse also reflected the influence of vegetation on bank stability. The channel is extensively tree lined and in many cases the binding effects of tree roots resisted bank failure, even where undercutting occurred. The stabilising effect of trees was most pronounced upstream of the knick-point where the banks were only subject to changes in water depth and flow velocity. Downstream of the knick-point, undercutting was more prevalent and the reduction in water level and greater loading by trees destabilised the river-bank. Bank top trees acted like levers, gradually pulling the bank toward the river channel.

A second factor that limited bank erosion was the presence of old stone bank reinforcement and accumulations of debris at the toe of the banks in many places. In some instances this toe material also appeared to be remnants of the pre-collapse bed, which was not removed by knick-point migration. The material gave some protection to the banks.

Bed and bank erosion released sediment and increased sediment transport downstream. Fine sediment release was transported long distances downstream during the flood event. The majority of coarse sediment (bed load calibre) released by erosion was deposited immediately downstream of the weir where the channel is relatively wide. Here the reduced flow energy resulted in sediment deposition and the formation of exposed gravel/cobble bars (**Figure A3.3**). Some material, especially smaller gravels, was transported further downstream, but was insufficient to generate appreciable aggradation. Material appeared to be distributed relatively evenly along the channel.

A3.2.3 Subsequent adjustments

A site visit 12 months after failure revealed relatively modest channel adjustments following an intense phase of adjustment. Further bank adjustment had occurred downstream of the knick-point, encouraged by trees destabilising the river-bank. The knick-zone was less obvious, having become more dispersed and as a result shallower in gradient, but it had not progressed further upstream.

A3.2.4 Conclusions

The geomorphological adjustments recorded upstream of Wall Nook demonstrate that a range of factors determine the extent of channel adjustment. When predicting the risk associated with weir collapse (or planning a weir removal), it is prudent to assess the length of the impounded reach, which reflects the extent of the upstream influence of the weir. At Wall Nook, discernible morphological adjustments were restricted to the downstream half of the impounded reach and corresponded to the extent of knick-point migration. Upstream of this, changes in water depth and flow velocity were insufficient to overcome the stabilising role of trees and remnants of bank reinforcement.

The adjustments reflect the fact that the influence of a weir on channel morphology diminishes with distance upstream and in this case was limited in the upstream half of the impounded reach. Sediment accumulation upstream of the weir, subsequently removed by knick-point migration, was also restricted to this extent. Channel adjustments in the downstream half of the impounded reach were also influenced by other factors including river-bank sediment properties and tree growth.

The impacts of an uncontrolled weir collapse such as this provide a useful illustration of the potential adjustments that can occur because of weir removal. In the case of weir collapses, the majority of channel adjustments occur during the hydrological event responsible for the collapse. Adjustments associated with controlled weir removals will tend to be less extreme as removal occurs at lower flows than a collapse and can be relatively prolonged as the channel adjusts more gradually to removal. Over time, as floods pass through the reach, the eventual outcome is likely to be the same.

A3.3 WOOLER WATER, NORTHUMBERLAND

A3.3.1 Introduction

Wooler Water is a river that flows from the Cheviot Hills through the market town of Wooler, 25 km south of Berwick-upon-Tweed, Northumberland, before crossing the low-lying Millfield plain to join the River Till. Between the 1930s and early 1970s, the river upstream of Wooler was severely affected by in-channel gravel mining over a distance of about two kilometres. A large flood in 1971, coupled with the effects of gravel mining, led to pronounced channel incision and damage to infrastructure.

In response, a channel stabilisation scheme was implemented upstream of the gravel extraction reach between 1971 and 1972. A section of the channel was re-aligned onto a straighter and narrower course and nine check weirs were installed, comprising driven steel sheet piles capped with concrete. After several flood events, the check weirs have gradually deteriorated, losing their concrete capping, bending under sediment load and separating from the river-banks due to erosion (**Figure A3.4**). At the upstream end of the straightened channel, widening and lateral adjustment occurred, accelerating considerably in the last decade.

Figure A3.4 Second and third check weirs in poor condition

A3.3.2 Existing situation

Large floods in September 2008 and July 2009 (with estimated peak flows of one per cent annual exceedance probability) triggered significant channel adjustment in the upper reach. The 2009 flood caused the most pronounced change, partially burying and outflanking the first (uppermost) check weir by up to 23 m (**Figure A3.5**).

A subsequent flood in September 2012 caused further bank erosion and outflanked the second weir. Interestingly, the wetted channel switched course during this flood and reoccupied its original course, exposing the partially buried check weir (**Figure A3.6**). Ongoing bank erosion is beginning to outflank the third weir.

A3.3.3 Implications

The 1970s channel stabilisation scheme was effective in this reach for nearly 40 years (although bed incision continued downstream), despite failing to address the underlying cause of instability in-channel gravel extraction downstream. This may be, in part, due to the lack of large floods during this period. The 2008 and 2009 floods were the largest in the catchment since the Great Border Floods of 1948 and 1949, to which they were comparable in severity. Now in poor condition, the check weirs continue to regulate river bed level, but are increasingly ineffective at controlling lateral adjustment and are outflanked as channel adjustment initiated by large floods progresses downstream.

Wooler Water is part of the River Till SSSI and SAC. The SSSI condition is classed as 'unfavourable', primarily due to the physical state of the river channel, and a river restoration strategy for the catchment aims to improve this (Natural England *et al*, 2003). Dealing with the

legacy of gravel mining and channel stabilisation structures, while a challenge, presents an opportunity to develop a more sustainable long-term solution.

A3.3.4 Conclusions

Check weirs used for channel stabilisation do not necessarily solve the underlying problem. Even the most effective check weirs only delay problems associated with channel instability until these reach the end of their design life and fail. Careful consideration should be given to assessing whether check weirs are appropriate, especially in high energy, upland gravel bed river systems. Robust design and construction, and careful attention to how the weirs are tied into the river-banks will ensure longevity.

Figure A3.5 Check weir outflanked and partially buried by 2009 flood

Figure A3.6 Check weir re-exposed by 2012 flood

A3.4 KIRKHAM, NORTH YORKSHIRE

A3.4.1 Introduction

The River Derwent, North Yorkshire is a lowland river with water levels artificially elevated by a series of impounding structures. It is thought that there has been a weir at Kirkham for over 900 years. The existing weir replaced an earlier mill weir and was constructed around 1710 as part of works to make the Derwent navigable, including the creation of a lock by enlarging the former mill leat. Navigation ceased in 1935 and in the 1950s the Ouse (Yorks) catchment board replaced the lock with a wider section of channel and two sluices to regulate water levels upstream during floods. Following the construction of flood defences at Malton in 2003, the Kirkham sluices played no further role in flood risk management.

As a SSSI and a SAC, the river faces a range of pressures arising from river and land management. A review was undertaken to identify whether the condition of the river could be improved by adapting or modifying structures.

A3.4.2 Trial lowering

Hydraulic modelling predicted that removing the weir and sluices at Kirkham could lead to significant environmental benefits by making the river more natural.

A water level lowering trial was undertaken in September 2014 to verify the model predictions and evaluate how the river might change if the structures were modified. The trial period was dry with relatively low flows and constant discharge. Kirkham weir sluices were lowered incrementally over 10 days, firstly from the normal level of 20 per cent open to 30 per cent open, then by a further 10 per cent every other day to 70 per cent open. At the end of the trial, a water level reduction of 1.1 m at Kirkham translated to 0.35 m at Malton, 11 km upstream. This was two kilometres further than expected and demonstrated the extent of habitat improvements that could potentially be achieved.

A3.4.3 Bank adjustments

The trial triggered changes to the river-banks in 49 locations, affecting a total of 782 m or 3.6 per cent of the 22 km of river-bank affected by the flow trial. The scale of the bank changes, in terms of length and proportion of river-bank face affected, varied considerably over the 11 km reach.

The bank adjustments were classified into a geomorphological typology, which reflected the scale (and also severity) of the impact. This was used to evaluate the geomorphic impact of the trial, determine the controls on bank response to water level changes and predict the likely impact of any future changes in water level. The bank adjustments fell into two broad categories and five types (**Table A3.2**):

- **Types 0 and 1:** adjustment arising from the settlement of reed bed or sediment deposits within the channel. Type 1a involved marginal reed beds which are aquatic habitats and Type 1b exposed dry deposits within the channel that are often covered by a mixture of aquatic and terrestrial vegetation.
- **Types 2 and 3:** displacement of blocks of river-bank sediments causing a change in the river bank.

Bank adjustments were evenly distributed throughout the impounded reach. The distribution of types showed some spatial clustering, albeit with exceptions:

- Type 1a adjustments clustered in the middle reaches where marginal reed beds were most prevalent.
- Type 1b adjustments tended to be located in the upper half of the impounded reach where berms were more common.
- Type 2 adjustments dominated the middle to upper reaches of the impounded reach.
- Type 3 adjustments were dominant in the lower portion of the impounded reach, suggesting that depth of impoundment and the degree of water lowering was a key influence on the scale of bank adjustment.

Aside from this, the spatial distribution of bank adjustments and the length of individual ones did not yield any convincing insight as to the factors influencing the degree of adjustment.

Table A3.2 Typology of observed river bank changes

Type	Description	Illustration
0	Subsidence of the marginal reed bed, but no effect on the river-bank. While this gives the impression of a change in the river-bank environment it does not constitute change in the actual structure. This lack of a change shows that the river-bank and reed bed were separate and not structurally connected across a transition. Indistinguishable from seasonal changes in the extent and height of in-channel vegetation, and not assessed further.	
1a	Vertical displacement of marginal reed bed created a distinct separation between the terrestrial environment (vegetation and sediment) and aquatic environment (vegetation and sediment), which was previously a gradual transition. This involved the formation of a distinct crack or movement plane creating a vertical bank face exposing sediments.	
1b	Vertical displacement of marginal exposed vegetated channel deposit (berm) created a plane of movement along (or close to) the true bank line. This involved the formation of a distinct crack or movement plane creating a vertical bank face exposing sediments. As with Type 1a this created a separation between the in-channel environment and the floodplain along the line of the river-bank.	
2	Vertical and/or lateral displacement of a block of river-bank (floodplain sediments) within the bank zone, ie the line of movement (failure plane), was located below the river-bank top (break of slope). This did not result in a retreat of the bank top, but a change in the profile of the bank face. In some locations this resulted in a movement of the bank toward the river.	
3	Vertical and/or lateral displacement of a section of river-bank with the failure plane located beyond the bank top, within the floodplain. This result in the landward movement of the bank top (break of slope).	

The number and extent of each type of bank adjustment is summarised in **Table A3.3**.

Table A3.3 Summary of observed bank adjustments

Type	Number	% of total number	Length (m)	% of total length of adjustments	% of total bank length
1a	6	12.3	62.2	8	0.3
1b	7	14.3	108	13.8	0.5
2	18	36.7	271.5	34.7	1.2
3	18	36.7	340.4	43.5	1.6
Totals	*49*	*100*	*782.1*	*100*	*3.6*

A3.4.4 Controls on bank adjustment

The relatively low proportion of the total length of river-bank that experienced changes, the pronounced variation in the scale of impacts recorded and the juxtaposition of different types of river bank adjustment, indicated that a range of factors influenced the response of the river-bank to water level lowering, including:

- bank slope
- undercutting of the banks
- pre-existing failure – line of weakness/ movement re-activated
- pre-existing line of separation (plane of weakness)
- settlement of marginal reed beds or in-channel deposits (berm)
- loading of bank by trees
- local waterlogging/high water table
- livestock damage.

The role of these factors varied from location to location and in some locations adjustment occurred due to more than one factor.

These factors illustrate that antecedent conditions play a key role in determining whether a section of river-bank will respond to water level changes. Despite the presence of Kirkham weir and the relatively low gradient (low flow energy) of the river, the channel has changed over time and this history of change influences the sensitivity of the river-banks. Changes to the river channel stem from a combination of natural river processes including flow and sediment movement and storage, and also vegetation growth succession through time. In addition to these natural changes, disturbance to the bank environment, especially by livestock, also influences the likelihood of adjustment. The occurrence of different types of adjustment tended to reflect different antecedent conditions (**Table A3.4**).

A3.4.5 Implications

The water level lowering trial offers an insight into river responses, especially in lowland situations, and reveals that water level changes alone (changes in flow velocity did occur, but were relatively modest) can generate bank adjustments over a relatively long reach.

This has a number of implications for weir removal projects. River re-naturalisation associated with weir removal will generally involve some bank re-adjustment as flow and sediment transport processes respond to the absence of water impoundment. Bank adjustments can arise through several different processes including water level lowering, changes to flow patterns and velocities over time and bed erosion. Often these occur in tandem and it is difficult to distinguish which processes are most important.

In the event of structure removal it is likely there would be two phases of bank adjustment:

1 An initial phase during which the banks adjust to generally lower water levels and the loss of the stabilising effect of high water levels enabling de-stabilising factors to promote adjustment.
2 A longer second phase during which variations in flow depth and velocities over space (as new flow patterns establish) and time (as discharge varies in response to rainfall) lead to localised areas of further bed and bank adjustment (erosion).

This flow trial has given a valuable and potentially unique insight into the potential role of water level lowering in the absence of fully re-naturalised flows.

It highlights the factors that control bank response to water level lowering associated with weir modification and removal. The results demonstrate considerable complexity which makes predicting the precise impact of water level lowering (such as due to weir lowering or removal) challenging. However, the impacts and controlling factors observed during the flow trial provide a basis for evaluating the likelihood of river-bank response to water level lowering. It is important to remember that bank adjustment is often part of the process of river re-naturalisation following weir removal. Where the risk posed by bank adjustment is not acceptable then measures to mitigate can be targeted where necessary.

The trial was designed to involve a relatively gradual lowering of the water level (within some timing constraints) to minimise the risk of bank adjustments. Anticipated bank change was expected to be predominantly of Type 1 and Type 2 style.
It is possible the process of water lowering was not gradual enough and that slowing this processes may have reduced the effect of the water lowering. Often

gradual lowering is seen as a means of reducing risk associated with weir removal. However, observations made during the flow trial as to the timing of the bank adjustments suggest that in some cases there existed a threshold water depth below which bank instability was triggered, but there was insufficient data to be specific. There is evidence that in different locations the threshold water depth (degree of water lowering) is different. These thresholds of stability mean gradual lowering may not necessarily provide a means of limiting bank adjustment.

This flow trial provided an insight into the likely distribution and scale of bank impacts, and also a strong steer as to the de-stabilising factors that should be taken into consideration when evaluating the ecological and financial impacts and benefits of weir modification or removal. Determining the relative risk of bank erosion will enable contingency plans to be developed to mitigate such risks. Measures can be developed to support and protect certain sections of river-banks to reduce risks associated with modification or removal, if these options are pursued.

A3.4.6 Conclusion

Bank adjustment is not an adverse impact from a geomorphological perspective. It becomes problematic when it affects land use or sensitive ecology.

Table A3.4 Factors influencing type of bank adjustment

Type	Typical antecedent conditions promoting adjustment
1a	Marginal reed bed connected to the river-bank and floodplain via a vegetation and sedimentological transition. Separation (creation of a failure plane) tends to occur where the reed bed is relatively wide (projecting into the channel).
1b	Berms likely to settle where loaded by trees or water retention in berm as river level falls. Berms that subsided tended to be those with a lower proportion of terrestrial vegetation indicating higher water content within the sediments.
2	Adjustment of the bank face often occurred where river-banks were steep particularly at water level. Type 2 adjustments occurred where tree lining was absent and often occurred in locations where the banks were subject to damage by livestock (grazing and trampling). In some locations, fresh bank adjustments involved re-activation of older, previously stabilised bank slips initiated by water level fluctuations during past flood events. Lines of weakness (old failure planes) are readily re-activated. Benching of river-banks can be indicative of past failures and provide an indication as to locations that are likely to be sensitive to water level changes.
3	Large bank adjustments extending beyond bank top reflect rapid drawdown of water level adjacent to the previously submerged river-bank. Where groundwater levels were high and the soil of low permeability, pore water pressures in the river-banks remained high following drawdown. Undrained soils with high pore water pressures have low shear resistance. Loss of the passive resistance imposed by the impounded water against the river-bank reduced the resistance to shear stresses within the bank leading to slippage and failure in some locations. Loading of the banks by large mature trees, especially where these were located along the very edge of the river-bank. In many cases, however, the presence of trees did not lead to bank adjustment and it is likely that other factors such as steepening or undercutting of the banks below the water level played a role.

A3.5 AFON ARAN, GWYNEDD

A3.5.1 Introduction

Dolgellau is located at the confluence of the Afon Aran and the Afon Wnion, which is an important salmon, sea trout and eel river. The town is at risk of out of bank flooding from the Afon Wnion and overflow flood routes from the Afon Aran. A weir on the Afon Aran immediately downstream of a low bridge (Pont Aran) had trapped gravel behind it since its construction in the 1800s, which raised bed and water levels in the Afon Aran and affected flow through the bridge (**Figure A3.7**). In 2014, the weir was removed as part of a wider flood risk management scheme.

A3.5.2 Options appraisal

Options for managing flood risk specifically from the Afon Aran were affected by a range of constraints. Working space for construction was limited by properties close to and forming part of the river channel, including listed buildings. The roads in the area are narrow and busy with many local businesses, and a lot of pedestrian traffic. Services are present in the bridge, which has been previously widened, and a sewer runs beneath the weir. The Afon Aran is also a salmon, sea trout and eel fishery and known areas of importance for spawning were present at the construction works site. Hydraulic modelling showed that the weir and associated raised bed behind it increased water levels by up to one metre during floods, potentially causing overtopping of low sections of river walls upstream.

There were two feasible options for managing flood risk from the Aran the raising of the existing river walls and/or weir removal. Factors considered included geomorphological risks, services, existing structures, construction disturbance (to the river and local community), archaeology, visual impact, fisheries, costs, construction methods, and health and safety. Guidance by Elbourne *et al* (2013) was used to identify the topics for consideration.

The preferred option was weir removal, which offered several short and long-term benefits and opportunities:

Figure A3.7 Afon Aran downstream of Pont Aran before (a) and after (b) works

- WFD compliance with restored natural hydromorphology and improved fish and eel passage
- reduced impact on built heritage and visual amenity
- opportunity to introduce more natural river features
- shorter construction phase and lower construction impacts
- existing standard of protection maintained during construction
- consistent with NRW (2016) aims and objectives.

Weir removal was not without impacts or risks, which included:

- **Sediment and water quality:** short-term impacts during construction were mitigated using silt control fencing. Sediment plumes were created during the most intrusive works, although monitoring indicated that these dispersed quickly.
- **Fisheries:** short-term impacts on fish during construction were mitigated by fish rescue, appropriate timing of the works

and the creation of features suitable for in-channel habitats, developed with the local fisheries officer.

- **Services:** short-term risk of damage to a sewer beneath the weir during construction. These were protected by confirming location at start of works then either avoiding or minimising excavation depth.
- **Built heritage:** while consultee feedback was generally positive, some comments indicated that the weir formed part of the 'character' of the area. A historic study of the weir and adjacent walls was undertaken and archaeological records were made.
- **Geomorphology:** low risk of unpredicted long-term changes to sediment transport, erosion and deposition. Basic sediment transport analysis and sediment transport screening was undertaken and visual post-construction monitoring was undertaken for the first six months and is recommended to continue.
- **Waste and invasive species:** Japanese knotweed was present and had to be managed. The majority of excavated river gravel was reused on site after being segregated by size and suitability and stored in a compound 500 m from works.

A3.5.3 Design

A non-technical briefing note was prepared for local consultees to explain the flood risk from the Aran, and describe the risks and benefits of each option allowing further discussions, and to reach agreement on a preferred option. This included consultation with NRW technical specialists (fisheries and biodiversity, geomorphology and environmental), as well as Snowdonia National Park Authority, the Town Council and Heritage Group. Letter drops were undertaken to all properties (residential and commercial) during design and before construction.

During design, a limited site investigation (hand-dug trial pits) was carried out within the river to determine depth, volumes and size of sediments, to locate the sewer within the weir and establish erosion protection required to existing structures. The design for reinstatement of river bed features was based on a series of features deemed important by fisheries such as shallow and deeper areas, flow speeds, and broken sight lines by boulders (**Figure A3.8**). Design of erosion protection for structures including the adjacent walls and bridge foundations was based on model outputs, the site investigation and information about the visual appearance of the structures.

A3.5.4 Construction

The weir was removed as permitted development in advance of the main flood scheme construction, during September and October 2014. The timing of the works was primarily chosen to meet fisheries-related timing constraints, using site-specific species traffic lights developed by the NRW fisheries officer. This involved identifying high, medium and low risk to each species for each month of the year, coded red (avoid), orange (avoid if possible), and green (best timing). This system was used to identify timing windows that were as green as possible across the range of species present and avoid any 'red' times. It indicated that in-river work needed to be completed by mid-October to minimise risks to fish and eels.

It also avoided working in the winter period most susceptible to high flashy flows, which would be a health, safety and environmental risk. Temporary works including flow pipes were required to provide working areas that were as dry as possible (given the permeability of the gravel bed), and straw bales and geotextile barriers were used to trap sediment.

Engineering supervision was carried out two to three times a week. An environmental Clerk of Works (CoW) carried out audits against the environmental action plan, and a geomorphologist also visited the site at key stages to inform the removal of sediment and reinstatement of the river bed features. An archaeological record was made of the weir removal and remnants of the weir were left in place on each bank to denote its location. The works were in full view of the public and considerable interest was generated locally.

A3.5.5 Lessons learned

- Post-scheme visual monitoring and feedback indicates that in addition to reducing flood risk, weir removal has created greater diversity in the river bed including areas of fast, shallow flow and deeper pools, and that wildlife and birds are using the river bed features. A fish survey has not yet been undertaken, but the site is a routine eel monitoring site for NRW so it will be surveyed in the future.

Figure A3.8 ***Afon Aran upstream of Pont Aran before (a) and after (b) works***

- A reduction in noise due to falling water was one of the unexpected impacts of the scheme and is seen as a benefit by local residents.
- The erosion checks at the base of the walls are more visible than expected due to a drop in river level after weir removed, but are expected to naturalise in colour over time.
- Sediment sorting appears to occur over time and the bed is relatively stable.
- The bed reinforcement under the bridge has created (at low flow) a shallow and smooth chute, which is not ideal for fish passage. Designs have been produced to attach low-cost baffles to the face of the reinforcement to increase flow depth and roughness. This was only apparent after the finished levels were confirmed, but roughness elements could have been included in the design in hindsight.
- The scheme has highlighted the importance of consultation with residents, councillors and other stakeholders, and the challenges faced during construction while undertaking intrusive works in a confined and very public working area.
- Face-to-face contact between geomorphologist and site team was essential to communicate bed reinstatement requirements as these are not easy to show on drawings.
- In the future, long-term fish and eel surveys are to be repeated, and a visual inspection of sediment changes is recommended.

A3.6 RIVER IRWELL, MANCHESTER

A3.6.1 Introduction

Numerous weirs have been removed from the River Irwell catchment over the past five years as part of a project to improve the WFD status of the waterbody and its associated tributaries.

A3.6.2 Prestolee weir

Prestolee weir was formerly used for the purposes of abstraction for the adjacent mill, but was no longer used for this purpose and had fallen into a state of disrepair. The presence of bedrock within the reach locally was identified during a fluvial audit, which provided confidence in the response of the river following removal (see **Figure A3.9**). No mitigation measures alongside removal were required because of the presence of bedrock, which was considered robust to morphological change and potential erosion. Other weirs that had failed naturally in the system showed a low risk of significant sediment accumulation downstream following removal.

A3.6.3 Goshen weir

Goshen Weir was located within the Irwell catchment on the River Roch and was removed in 2012 by the Environment Agency. pre and post weir removal hydraulic habitat mapping was undertaken to monitor the geomorphological response to the removal (**Figure A3.10**). Note the characteristics of the river near to the weir after its removal. There is noticeable similarity in the river form upstream.

Figure A3.9 Prestolee weir before (a) and after (b) removal

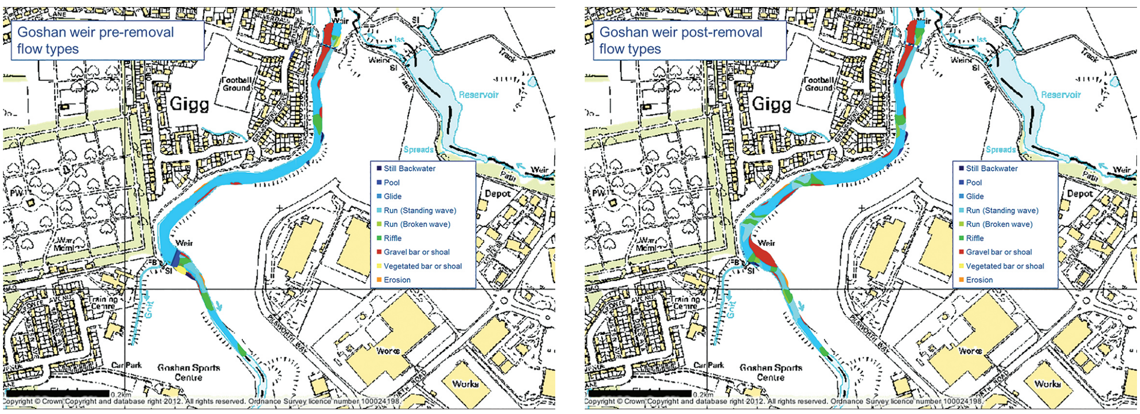

Figure A3.10 Flow types at Goshen weir before (a) and (b) after removal

A3.7 RIVER WANDLE, GREATER LONDON

A3.7.1 Introduction

The River Wandle in Carshalton, Greater London is classed as a 'heavily modified waterbody' under the WFD. The Wandle river restoration project aimed to restore the waterbody to good ecological potential by 2015 (as required by the WFD) and involved weir removal or lowering at two sites.

At Hackbridge in south-west London, four low head weirs were removed to restore fish passage and hydrogeomorphology, reduce impounded river length, create new marginal wetland habitat, and improve biodiversity and resilience. The works started in 2012 and cost £150 000. At Carshalton, one kilometre upstream of Hackbridge, a 1.8 m high former mill weir was lowered and the fish pass modified to restore fish passage to 500m of channel and restore habitat and geomorphological processes over 150 m. These works were completed for £100 000 during the summer of 2014.

The schemes were promoted by the South East Rivers Trust (incorporating the Wandle Trust) with support from Defra Catchment Restoration Fund, Environment Agency, Heritage Lottery Fund, Living Wandle Landscape Partnership, London Borough of Sutton, Rydon Construction and Thames Water River and Wetlands Community Days fund.

A3.7.2 Hackbridge weir removal

Four weirs (less than 0.4 m high) were removed at Hackbridge to restore fish passage and hydrogeomorphology, reduce impounded river length, create 1000 m^2 of marginal wetland habitat, and improve biodiversity and resilience (**Figure A3.11**).

The design was developed in conjunction with 2D hydraulic modelling to avoid increasing flood risk. This took longer than expected due to the complex nature of the site, but was an important consent requirement.

Figure A3.11 River Wandle at Hackbridge before (a) and after (b) weir removal (courtesy South East Rivers Trust)

Construction started with removal of old toe-boarding from the perimeter of the island and re-profiling of the island. A new bank-line was created using hazel faggot bundles secured with chestnut stakes and backed with coir netting, and excavated sediment from behind the weirs was placed behind the new bank-line (**Figure 3.12**). Weirs on either side of the island were then removed simultaneously, reducing the impounded river length by 300 m, and a 125 m length of river channel narrowed using a combination of chestnut stakes, hazel faggot bundles and stones. A causeway and backwater were constructed using coir geotextile over a bed of stone, weighed down with gravel and sediment, and planted with aquatic vegetation. The new banks were re-graded to a gradual slope and also planted with a variety of aquatic vegetation. Diversity in [channel] depth and width, habitat and flow regime was introduced by importing 250 tonnes of gravel, and large wood to the new sinuous channel.

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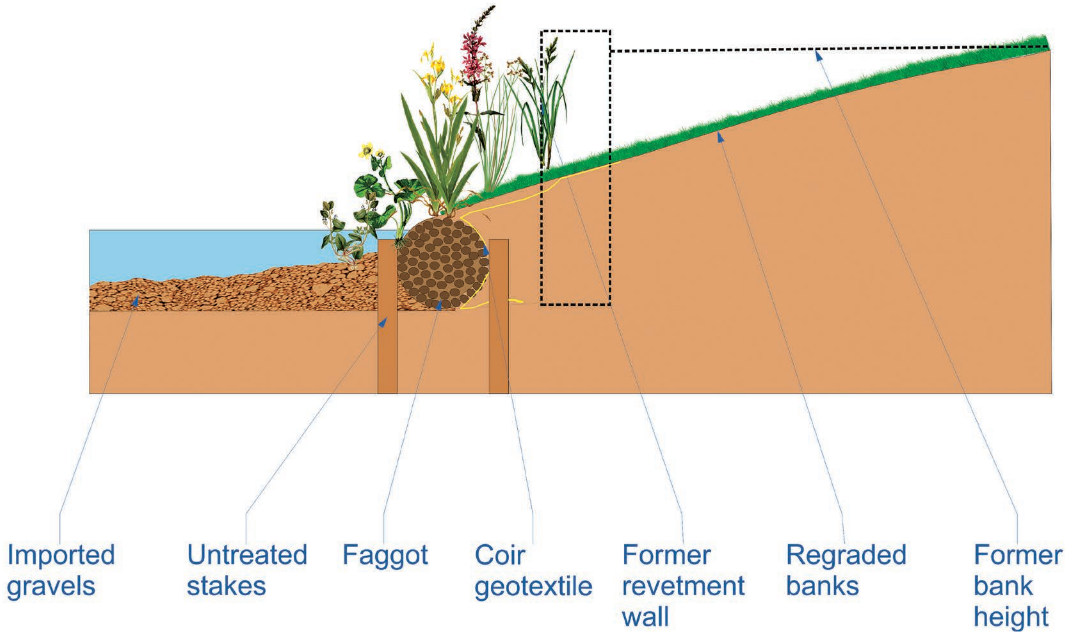


Figure A3.12 Bank softening at Hackbridge (courtesy South East Rivers Trust)

The site is heavily urbanised and proactive stakeholder consultation identified a broad range of needs and opinions. In particular, when local residents emphasised the visual amenity provided by a large body of water created by the weirs, the scheme was re-designed to include a large backwater, giving additional benefits such as habitat creation and recreation (eg model boating). A local developer also agreed to erect a pond-dipping platform on the backwater to create a community asset. Local engagement led to the involvement of the neighbouring communities as volunteers, which escalated as word spread, breaking down barriers between social groups. Indeed, a team of 60 volunteers planted 6000 plants over three days.

Buried services crossing the river and island included gas, high and low voltage electricity, a water main and sewer. Although some of the electricity cables were redundant, these had to be avoided until the utilities company could attend the site to locate, identify and either disconnect or remove the service, leading to delays in accessing some areas of the site.

A public footpath and cycle route through the site were temporarily diverted with access restrictions for all. The importance of implementing signage and diversions from day one was emphasised when a wheelchair user attempted to use the (not yet signed) footpath.

Site security was a concern as the project formed part of a wider urban regeneration scheme and as local residents were relocated the neighbourhood became less inhabited over time. Out-of-hours security was employed to reduce the risk of unauthorised entry to the site.

An unexpected benefit of weir removal was the elimination of noise nuisance to local residents caused by debris trapped in the weir pool banging against the cast iron plate weir.

A3.7.3 Butter Hill weir lowering

The 1.8 m high weir at Butter Hill, Carshalton was lowered by one metre, reducing the length of impoundment by 150 m (15 per cent of total waterbody length) and restoring natural flow to the upstream channel. An existing Larinier fish pass was also modified to improve efficiency and open up fish passage for 500 m upstream (50 per cent of the waterbody length). In addition, a total of 500 m of river was narrowed, re-meandered and re-naturalised (**Figure A3.13**).

Hydraulic and flood risk assessments were carried out to assess the impacts of the work. Although full removal of the weir was desirable from a river restoration perspective, lowering was the preferred option due to concerns about maintaining heritage and the structural integrity of adjacent river walls and buildings. Wing walls and braces were installed to enhance structural support with the weir at its lowered height.

Figure A3.13 River Wandle at Butter Hill before (a) and after (b) weir lowering (courtesy South East Rivers Trust)

Upstream of the weir, the over-straight, over-wide channel was narrowed and modified to create a meandering sequence using a combination of gravel, hazel faggots, chestnut posts and coir geotextile, with silt from the channel and brash as backfill. Both banks were re-graded to create marginal and transitional habitats. A variety of marginal plant species were introduced to assist with naturalisation, by a team of 15 volunteers who planted 2000 plants and coppiced trees to improve light penetration.

Downstream of the weir, the channel was narrowed and re-meandered to create a low-flow channel, berms, riffles, pools and marginal wetlands over a 350 m length, improving the resilience of the river to extreme weather and river flows. About 300 tonnes of gravel were added to restore natural hydromorphological processes and large wood was introduced to further diversify the river flow, replicate natural processes now constrained in an urban environment and create habitats for invertebrates and all life stages of fish. Trees were also removed in phases over a two year period to increase light in selected places and encourage plant growth along the whole 500 m reach.

Although the project benefitted from local council support, stakeholder consultation was essential to its success. The site is urban, located in the middle of a housing estate with houses on both sides of the river, next to a road and a well-used footpath and cycle path. There were high levels of interest in the project providing good opportunity for engagement. However, this could be time-consuming at times. Key to the success of the project was providing information in the form of leaflets delivered to residents and posters around the area. Some initial anti-scheme action via social media was encountered, but a site meeting with the parties concerned was influential in changing opinions, and public information posters, flyers and word-of-mouth generated an increasing level of local support and volunteer involvement over time. Also, the occupiers of residential properties overlooking the site acted as an unofficial 'neighbourhood watch' for the site.

The works were delivered by the South East Rivers Trust (incorporating the Wandle Trust), specialist contractors and a team of volunteers. Weir lowering and fish pass removal/replacement were funded separately and so were awarded as separate

contracts, running in parallel, with shared use of the site compound. Volunteers undertook planting and vegetation management on completion of the construction works.

During construction, wet weather towards the end of the project increased the risk of transferring mud from the site to surrounding roads and footpaths. Careful site management reduced the number of plant movements from site to public highway and regular manual cleaning using shovels and brushes reduced the transfer of mud to the road, avoiding the need for road sweepers.

One unintended benefit is that local people can now hear the sound of the river as it moves over gravel riffles and around the large woody material before they can see it when walking along a nearby footpath. This draws people in to the river and is seen as an attractive benefit.

A3.7.4 Lessons learned

Weir lowering may be more suitable than removal to balance conflicting requirements. It can still improve fish passage, reduce impounded river length, restore hydrogeomorphology and increase habitat, biodiversity and aesthetic value.

Weir removal can remove nuisance due to noise in some cases.

Stakeholder engagement can inform the design and generate additional benefits. It can also lead to significant local support, engage new volunteers and break down social barriers.

A3.8 BUXTED PARK, EAST SUSSEX

A3.8.1 Introduction

The weir structure at Buxted Park was highlighted as one of the main obstructions to multi-species fish passage along the River Uck, the main tributary of the Ouse in East Sussex. In 2011 the Ouse and Adur Rivers Trust (OART), funded by the Defra River Improvement Fund (see **Websites**), removed the weir boards to monitor what would happen to the nearby fishing and ornamental lakes that form part of the Buxted Park Estate and were believed to be fed from the river. Having regularly checked the levels and following some repair works to one of the retaining weirs within the lake network it was clear that the weir could be removed without any detriment to the lakes.

The weir removal and river restoration work was undertaken as part of a project delivered by the Environment Agency, Ouse and Adur Rivers Trust and Royal HaskoningDHV (OART, 2011).

A3.8.2 The works

A nature-driven design philosophy was adopted to develop the designs for the Buxted Park weir removal project. In this instance, landowner support and the relative lack of significant assets in the floodplain meant that design remained minimal, with natural processes allowed to operate.

The removal of the weir entailed limited bed and bank profiling at the site of the weir, in areas that were formerly part of the structure. The physical removal of the structure was completed in March 2013 following heavy rain at the end of 2012, which meant working in the channel became too dangerous.

The footings of a nearby bridge had to be protected with gabion baskets to ensure that it remained *in situ* as the upstream banks began to slump (**Figure A3.15**). A steep bank adjacent to a public footpath and ornamental fishing lakes was stabilised using live willow spiling to limit erosion and prevent the capture of the lakes (**Figure 3.15**).

Natural river processes were allowed to operate. The banks were allowed to collapse and have now stabilised. Gravel was seeded in strategic locations upstream of the weir and these have been reworked and integrated into bed and bar features alongside the natural coarse sediment load. The gravel was seeded in strategic locations in the channel (ie on the inside of bends) and allowed to re-work naturally. It has now been distributed throughout the channel by natural processes, forming a variety of lateral and medial bars.

Trees were planted along the banks to provide additional shading and, in the future, allow natural recharge of woody debris within the stream. At the request of the angling club the project also put gravel into the channel at various locations to provide habitat for fish spawning and invertebrates.

Figure A3.14 River Uck before (a) and after (b) improvement showing woody debris accumulation and re-establishment of vegetation

A3.8.3 Lessons learned

The impact of the project was almost immediate with chubb, sea trout and dace quickly identified in the upstream area. In addition there had been considerable slumping of the banks as the river was re-profiled and, by the beginning of 2015, the channel had narrowed, riffles and pools had formed, woody debris had collected within the channel and a variety of flow regimes had been established (**Figure A3.14**).

Buxted Park is now used as a demonstration site to show the positive impacts of weir removal and has seen visits from the RRC, the South East River Basin Liaison Panel and numerous other conservation organisations from the UK as well as visits from the Czech Republic River Restoration Centre and a non-governmental organisation (NGO) from Brazil who have secured funding to undertake Brazil's first river restoration project.

Websites

Ouse and Adur Rivers Trust: **www.oart.org.uk**

The Rivers Trust River Improvement Fund: **www.theriverstrust.org/projects/sepp/index.html**

The re-profiled bank of the river channel with willow spiling shortly after construction.

The re-profiled bank and gabion baskets shortly after construction.

Stabilised, re-vegetated banks upstream of the weir.

Figure A3.15 River Uck permanent works

A3.9 PLEDGE'S MILL, KENT

A3.9.1 Introduction

The mill channel on the Great Stour, Kent was constructed about 500 years ago to provide a head of water to Pledge's Mill. By design the channel was of a low gradient to provide a head of water at the mill. A fixed crest weir and three sluices impounded the channel at the mill resulting in a slow moving flow and a barrier to fish passage.

A3.9.2 The works

The mill weir was lowered in 2013 in order to provide fish passage and to allow more naturalised flow conditions in the mill channel. Lowering was chosen rather than complete removal of the weir because upstream structures with shallow foundations relied on the presence of the weir for stability.

The existing mill walls had shallow foundations and so were shored up with faced gabion haunches in order to accommodate the newly lowered channel (**Figure A3.16**).

Steepening of the channel upstream was limited by the presence of a sewer pipe in the river bed upstream of the weir. The costs of lowering the sewer were prohibitive, so hard protection had to be installed over the pipe, which limited the development of naturalised channel to the reach of the river between the weir and the sewer pipe.

Figure A3.16 Weir improvements

A3.10 WEIR X, GWYNEDD

A3.10.1 Introduction

Weir X is a flow measurement structure on the Afon Tryweryn, Gwynedd, North Wales. Until 2011, the weir design generated a deep recirculating current downstream of the structure with a strong towback (**Figure A3.17**). It was the site of a fatality in July 2005. Modifications to the weir were undertaken to improve safety.

A3.10.2 The problem

Weir X is located on a man-made section of the Afon Tryweryn, constructed in 1956 as part of the Bala Lake Scheme. The straight, uniform upstream channel was designed to create smooth subcritical flow conditions on the approach to the gauging weir, and is confined between raised flood embankments.

The broad-crested compound weir comprised a 23 m wide central low-flow crest flanked by 25 m long higher relief crests. The downstream face of the weir was near-vertical. Water level difference across the weir was typically 700 mm.

The hazard at the weir was significant. A deep, uniform recirculating hydraulic formed downstream of the weir due to its near-vertical downstream face and substantially wider stilling basin (this increased the width causing additional hazards by generating eddy currents to feed flow back into the hydraulic). The hydraulic was quiet and looked benign. The river-banks were steep and consisted of rock armour, making access or egress difficult. All of these factors made it difficult for a person or other buoyant object to escape from the hydraulic jump or to implement a rescue.

Flow (and hydraulic hazard) at the weir varies considerably. Flow in the Afon Tryweryn is controlled by releases from Llyn Celyn reservoir eight kilometres upstream. Minimum compensation is 0.368 cumecs in winter and 0.737 cumecs in summer. The river is regulated 365 days a year meaning that flows passing Weir X can vary on a daily basis. Of particular note, flows in the summer months passing Weir X can be uncharacteristically high.

Figure A3.17 Before modification

Figure A3.18 Physical modelling of proposed measures (courtesy Engineering Paddler Designs Ltd)

The risk of harm was exacerbated by the location of the weir near Bala town centre. The weir is readily accessible by visitors, including local children who have been seen to fish from the structure. There were also known previous near-miss incidents at the weir. The owner identified a need for change following a fatality in 2005.

A3.10.3 Option appraisal

The objectives of the work were to eliminate or reduce the hazard at the weir.

At feasibility stage, six initial options were compared using an appraisal summary table:

- do nothing
- replacement weir
- alternative flow measurement method
- stone infill downstream of weir
- modification of weir crest
- modification of weir crest and downstream flow characteristics.

The preferred option was modification of the weir crest and downstream flow characteristics. This involved extending the high-flow crest inwards, lowering a central portion of the low-flow crest, and installing concrete infill downstream of the low-flow crest to reduce recirculation. Technical viability was confirmed using simple hydraulic modelling software for the design and calibration of flumes and weirs.

The preferred option was progressed to detailed analysis and design. A 1:10 scale physical model was used to develop and verify the design. This included the weir, areas immediately upstream and the channel 40 m downstream. The model was calibrated against observed flows and levels (**Figure A3.18**). The model was used to assess the formation of a hydraulic jump and its retention capacity, determine the stage-discharge relationship and flow velocities upstream and downstream, and assess likely impacts on sediment deposition. 1D hydraulic modelling was used to assess potential impacts on flood risk.

Modelling showed that the most favourable combination of measures was:

- Lower a six metre central portion of the low flow weir crest by 220 mm to increase velocity and reduce the likelihood of entrapment.
- Extend the high flow crest inwards and reduce elevation by 340 mm to avoid increasing flood risk.

- Install a 7.6 m long concrete ramp (about 1 in 5) downstream of the low-flow crest to reduce deep recirculation and create a central jet of water.
- Install two islands with rounded faces and gentle slopes to increase flow depth immediately downstream of the stilling basin. These were 7.6 m long and 0.8 m high.

A3.10.4 Lessons learned

Physical modelling was invaluable in the development and verification of the weir modifications, and led to further measures that added considerable value to the scheme.

The designed weir modifications in combination with a shallow downstream ramp and downstream islands have provided essential improvements to safety.

There is no longer a deep recirculating current downstream of the weir. Water depths are always sufficient such that should a person pass over the weir structure they should flush through. The downstream channel has significantly lower velocities due to its extended width making egress from the channel possible.

A3.11 SHARPSBRIDGE, EAST SUSSEX

A3.11.1 Introduction

Sharpsbridge is a road bridge that crosses a bifurcated reach of the River Ouse, East Sussex, with each channel around the natural island passing through a culvert under the bridge. The solid concrete bridge footing acted as a weir, with a drop between the concrete slab and downstream water level acting as a barrier to fish passage (**Figure A3.19**).

An earlier attempt at rock placement downstream of the concrete slab to enable fish migration was not successful because high flows had repositioned the rocks. Remedial work was needed to improve fish passage at the site. This was achieved by adding a new rock ramp onto the northern arm of the river, reducing the drop in water levels through the culvert and allowing passage for a greater variety of fish species over a wider range of flows. The rocks also slow the flow and create broken water to attract fish.

The work formed part of a suite of schemes delivered by the Ouse and Adur Rivers Trust (OART), developed as a catchment-based partnership project between the Environment Agency, the OART and Royal HaskoningDHV (OART, 2011).

A3.11.2 The works

Work in the western arm was carried out in the dry, using temporary aquadams and pumping water to the northern arm. The existing rubble rock weir was removed. A 4.5 m wide rock ramp was constructed *in situ*, using granular fill and geotextile at the base, concrete at the southern end, and rock armour forming the surface of the ramp (**Figure A3.20**).

The project team were keen to use locally-sourced material, not only to fit in with the surroundings, but also to keep the carbon footprint of the project low. Unfortunately, however, the closest quarry could not provide material within the tolerances required to ensure long-term stability of the structure. Instead, Kentish ragstone (a hard, durable limestone) was sourced from a quarry in Kent to provide material for the main perturbation boulders.

Figure A3.19 Sharpsbridge before (a) and after (b) improvement

These boulders were carefully positioned and fixed in place in a concrete base (**Figure A3.22**). Smaller rocks were then set in place on top of the concrete to create a rough naturalistic surface. About 50 per cent of each perturbation boulder was buried to enable the structure to withstand the forces in the river. The boulders were placed approximately equidistant, with their height increasing upstream to provide a smooth gradient over the structure.

Following completion, signs were erected to advise canoeists of the rock ramp and divert them through the southern culvert, which remained unchanged.

A3.11.3 Lessons learned

- The project team drew upon good practice experience from Belgium and The Netherlands to help determine the best layout of the large boulders on the ramp.

1 2 3 A

- Carbon calculators were used, which highlighted the transport of materials as a high carbon cost. This led to the successful sourcing of local materials to construct the ramp.
- The works were successful. During low flows, the flow velocities between the perturbation boulders and the water depth are good for fish migration. At high flows, the river is much slower flowing over the high-flow channel, and sufficiently deep to allow fish passage.
- The project won a Sustainability and Environment Award in the Institution of Civil Engineers Project Excellence Awards 2013 and the prestigious Conservation Award (Professional Category) 2013 from the Wild Trout Trust.

Perturbation boulders placed on geotextile and granular base

Perturbation boulders fixed in a concrete base

Concrete and smaller rocks placed to provide a smooth transition with the upstream river bed.

Figure A3.20 Construction works in progress

A3.12 RUSHEY WEIR, OXFORDSHIRE

A3.12.1 Introduction

The Environment Agency owns, operates and maintains 195 weir sets across 45 weir and lock complexes on the River Thames bringing multi-functional benefits including river navigation, water abstraction, recreation, conservation, biodiversity and flood defence.

Paddle and rymer weirs impound water by means of boards (paddles) manually inserted into the river between vertical timber posts (rymers) (**Figure A3.22**). They are a development of 'flash locks' that were once used to allow river navigation before the introduction of pound locks. A section of the weir would be removed and river craft could be winched upstream through the resulting 'flash' of water (**Figure A3.21**).

A3.12.2 Operational issues

Heavy rain in the upper Thames catchment in July 2007 resulted in widespread flooding and highlighted operational issues with the nine remaining paddle and rymer weirs (P&R) on the River Thames. A review concluded that Environment Agency staff operating the weir were regularly required to lift weights (both static and live) three times above the recommended limits within the Manual Handling Operations Regulations 1992. This was particularly onerous during times of flooding, when operatives had to remove a large amount of weir apparatus in a short time. So a project to replace the weirs was initiated.

Key legislation includes the Health and Safety at Work etc. Act 1974 and the Manual Handling Operations Regulations 1992. Three ergonomic assessments demonstrated that the operation of the weirs placed staff at risk of at risk of serious muscular skeletal injury. These conclusions were challenged by English Heritage and the local community, but supported by the HSE, Department of Work and Pensions and National Audit Office (NAO).

A3.12.3 Heritage

As part of the Environment Agency's wider duties, an independent heritage review of all nine P&R weirs was undertaken. This concluded that four weirs were of higher value and suitable for listed building status. A third party subsequently made a listing application to English Heritage in March 2009, which resulted in three weirs being granted Grade II listed building status, including Rushey weir. The listing refers to the value of the historical mode of operation employed at the weirs.

A3.12.4 Rushey Weir

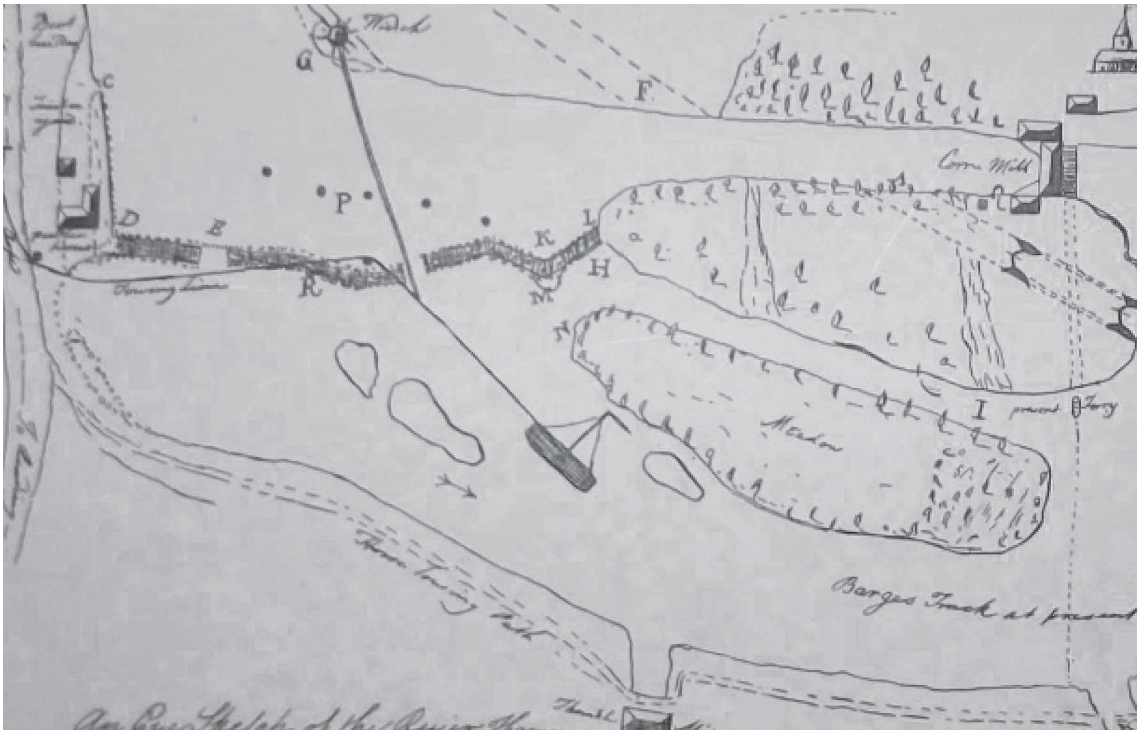
Rushey Weir is located in rural Oxfordshire and was originally constructed in 1790 and reconstructed in 1887. It consisted of steel frames either side of a concrete bullnose. The north section was 14.7 m wide (24 no 3 deep paddles) and the southern section was 6.25 m wide (10 no 3 deep paddles). The northern section was reconstructed again in 1932, but the southern section and bullnose were unchanged making it the oldest weir on the River Thames. There are also two Scheduled Ancient Monuments (SAMs) on the right bank. Divers' surveys carried out indicated that the weir structure was deteriorating rapidly and had about five years' of residual life.

A3.12.5 Option appraisal

The listed status of Rushey weir meant that the project appraisal process was significantly extended. A number of unusual options were reviewed that would have retained a fully operational P&R weir *in situ* as listed building consent was required from the LA. English Heritage became a statutory consultee. Several alternative options were considered, which included:

- gantries allowing lifting of paddles
- hinged system using winches
- new weir upstream or downstream retaining the P&R weir

Operation of a paddle and rymer weir



Operation of a flash lock for river navigation

Figure A3.21 Paddle and rymer weir, a development of 'flash' locks

- bypass channel incorporating the new weir
- mobile or fixed cranes
- lightweight materials
- replacement weir (fixed crest, radial gates, vertical lift (buck) gates).

All options except gated weirs significantly increased costs, were unproven, unsightly or introduced new risk.

Following this options appraisal, English Heritage accepted that the main weir operation could be with radial gates, provided part of the P&R apparatus was retained along with the weir bullnose, the fabric of which was particularly old. The agreed solution was a weir with three dipping radial gates and a single depth of lightweight P&Rs on a raised crest on the south side of the weir. To address the operational issues these P&R weirs are removed and installed on a yearly basis under an agreed operational protocol.

A3.12.6 Key design issues

Geomorphology	There are significant deposits of gravel downstream of the weir and the new weir will change the flow regime
Fish pass	Initially a technical pass was selected, but these tend to be effective for a limited range of species. Instead a nature-like meandering bypass channel has been constructed, improving passage for a range of fish species to 3.8 km of valuable flowing water habitat upstream. The shallow gravel habitat below the weir is important for fish spawning and changes to the weir flow patterns may affect this. Baseline surveys of the weirpool were undertaken and will be repeated over time to allow any impacts to be identified and made good.
Cofferdam/temporary works	To ensure flood risk was managed during the construction period the cofferdam design was reviewed to see whether it should be fully or partially removable in the event of a flood. Due to the rural location and limited properties at risk the agreed approach was to allow alternate piles to be removed.
Construction flood risk	A detailed flood protocol was put in place to define communications and actions during high flows
Hydropower	At the request of a local landowner, design tweaks were required in the construction phase to assist with the possible future provision of hydropower at the weir.
Archaeology	Due to the location of the two SAMs full excavation and recording was required before construction of the fish pass.
Access	The local community were very concerned about how the site was assessed, which was located about 2.4 km from any public roads. River access was not possible due to limited draught. A temporary access track was agreed across farmland which involved the introduction of speed limits on the local road network.

A3.12.7 Key construction issues

High flows	High flows resulted in flooding to the cofferdam in the first year and to the access road on several occasions.
Condition of existing structure	The condition of the existing weir was far worse than initially expected. After dewatering the weir, significant seepage was evident and there were concerns over stability of the bullnose structure. In the short-term this was stabilised by pumping material underneath the weir, which needed removing during the second season.

A3.12.8 Lessons learned

Community engagement	Common with many other projects 'how' the work is done, particularly regarding access, is becoming an increasingly important part of the engagement process. The local community had deep reservations over access, which was resolved through dialogue and regular updates, including site visit throughout the project.
Appraisal options	The listing and involvement of English Heritage resulted in a long appraisal process with health and safety specialists reviewing both the existing weirs and possible solutions. Sufficient time needs to be allowed for this.

A3.13 DOG HEAD STAKES WEIR, WEST BERKSHIRE

A3.13.1 Introduction

Dog Head Stakes Weir, seven kilometres east of Newbury, West Berkshire, maintains navigable water levels in the River Kennet as part of the Kennet and Avon navigation, and provides a head of water to supply a nearby Site of Special Scientific Interest (SSSI). The weir was constructed around 1810 from wicker hurdles placed against timber stakes driven into the bed of the river. The hurdles were removed during the winter period to allow floodwaters to pass unhindered and replaced during the spring to increase river levels upstream of the weir during low flows in the summer months. This practice ceased during the early 1950s as the canal fell into disrepair. The original structure deteriorated over the years, and the river bed at the weir progressively eroded.

In 1992, a temporary gabion weir was constructed, but due to financial constraints, the planned permanent replacement was never built. The temporary weir was unable to maintain navigable upstream water levels under low-flow conditions and required regular maintenance and repair (**Figure A3.22**). Also, during high-flow conditions, upstream water levels increased to the extent that they overtopped a lock downstream, causing operational problems and excessive flows in the canal.

In 2014 to 2015, a replacement weir, boom and bypass channel was constructed (**Figures A3.23 and A3.24**), with lock improvements to prevent flooding. The performance requirements were:

- Provide a navigable draught above the bottom cill at the upstream lock, for Q95 flow or 1:20 year drought (whichever is the minimum).
- Avoid raising water levels such that flow bypasses the lock downstream during floods up to 10 per cent annual exceedance probability.
- Maintain flow to the SSSI.
- Simple to construct and maintain.
- Provide a fish pass and comply with environmental legislation.
- Prevent craft from reaching the weir.

Figure A3.22 Temporary gabion weir

A3.13.2 Planning and design

Project planning and design was carried out in 2013 to 2014 and included the preparation of a hydraulic report and flood risk assessment. Hydraulic modelling was undertaken to inform design, assess changes in flow split between the River Kennet and Chamberhouse Draught (both SSSIs), and ensure that the new fish pass continued to operate during low-flow conditions.

Negotiations with landowners were an important element of the planning process. Land was purchased to allow construction of the fish bypass and provide an easement for future maintenance. Land was also leased to provide site access, works compound and the installation of Heli-piles at either end of the weir boom. Access for heavy plant was negotiated through the adjacent race course as a railway bridge imposed height and weight restrictions.

Flood defence consent was required for the new weir, boom, fish bypass, and lock improvements, along with fish pass approval, water transfer licence, planning permission, and consent from Natural England for work adjacent to a SSSI. The site is of historical importance and required an archaeology written statement of investigation, trial pits and core sampling before starting.

Tree felling was undertaken outside the bird nesting season. Construction took place during times of low flows, avoiding migrating fish upstream and in the main river.

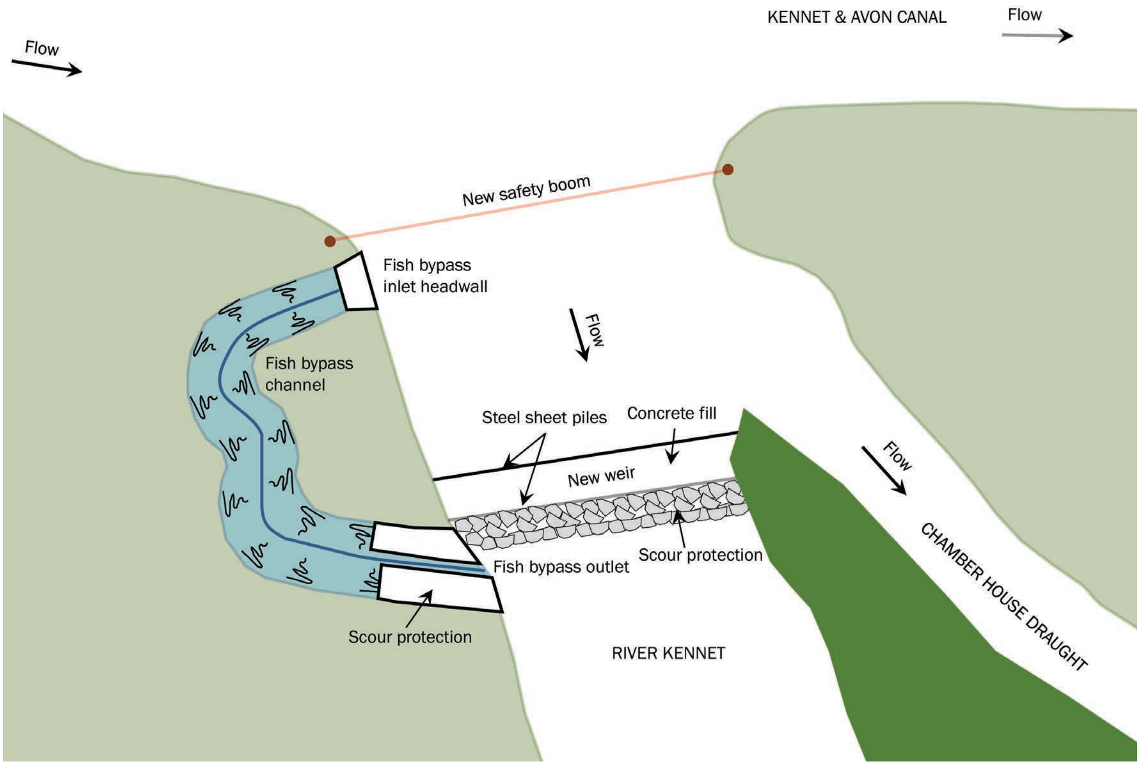


Figure A3.23 General arrangement

Figure A3.24 Weir approaching completion

A3.13.3 Replacement weir

The replacement weir was constructed in the same location and on the same alignment as the old weir, with a 26.8 m wide and 4 m long fixed crest. Two 100 mm high removable glass-reinforced plastic (GRP) boards formed a sharp crest at the required level for navigation, allowing safe inspection and maintenance, and giving some flexibility in water management if required.

The weir was formed by driving rows of 7 m long GU6N steel sheet piles upstream and downstream of the existing structure in two stages, with a driven length of 6 m (Figure A3.25). Stage one involved driving piles from the left bank to the river centreline. A sacrificial row of piles completed the box on the first half of the weir, allowing removal of the gabion baskets without releasing silt into the river. Gabion stone was left in place as

Figure A3.25 Replacement weir

fill and compacted, then the many voids and weir structure were filled with mass concrete. The piles were fixed to the concrete via shear links.

As well as forming the structure of the new weir, the mass concrete provided a working platform for plant to access and install the second half of the weir. The new weir encased the existing structure, minimising the amount of silt entering the river and disturbance of the river gravel bed. The piles were left high to avoid the need for temporary works and cut to size after concrete pouring.

A3.13.4 Fish bypass

A new fish pass was required as more than 50 per cent of the structure was replaced and the River Kennet is frequented by salmon and migratory trout. A bypass channel was designed in consultation with the Environment Agency with some adjustments during construction. This included strategically placed boulders, additional stone to the lower half of the channel and rip-rap added at areas prone to washout (**Figure A3.26**).

These improvements will also create diverse habitats in the pass for spawning and resting fish. Silt obtained from site was placed on the upper reaches of the banks as it contained reeds and other plant species to stabilise the channel. It is envisaged that by the end of the first growing season, the banks will have colonised naturally, with other indigenous species from the rich seed bank that exists within the reclaimed topsoil.

Figure A3.26 Fish bypass

A3.13.5 Other works

Sediments along the River Kennet have been shown to contain material of national and international archaeological significance. The riparian environment would have been an ideal hunting ground for Mesolithic hunter-gatherers who foraged and hunted using hand-made tools of flint and wood from 10 000 to 4500 BC. Any excavation on undisturbed ground had the

potential to uncover archaeological deposits and an archaeological written statement of investigation, trial pits and core sampling were required before construction could start. Trial pits were located on the proposed line of fish pass, which required significant excavation and an archaeological watching brief held at the fish pass head wall and at the outlet. However, no significant artefacts were found.

Some additional works were required due to access constraints on underwater assets, which prevented inspection before construction. Tree and vegetation removal was undertaken on the offside to install the Heli-pile for the boom and improvements to Widmead Lock were carried out, taking advantage of access and de-watering.

Construction was completed ahead of programme due to fine dry weather and low river flows, and within budget at around £575 000.

A3.13.6 Lessons learned

Estates agreements can be complicated and negotiations should start early to avoid delays. If contracts cannot be exchanged before works start, an early access agreement can allow works to progress as programmed, although this may incur additional costs.

Effective communication with all stakeholders is important. Not only does this reduce the risk of objections at consenting stage, but also opens up possible sources of expertise.

Detailed topographical surveys should be undertaken to inform accurate hydraulic modelling and design.

It is important to check with the LA whether the proposed works are on a site of historic importance. If so, archaeological work may be required that can affect both the programme and cost.

Weir boards were included in the design at a later stage. This was felt to be a good decision as they will provide a means of preventing water flow over sections of the weir for future inspection and maintenance. They will also allow the weir level to be adjusted slightly if unintended issues with the design level are found during use, preventing expensive remedial works.

A3.14 GREEN STREET WEIR, SPEYSIDE

A3.14.1 Introduction

The River Spey is judged as one of the great salmon rivers of Scotland and the fishery provides significant benefits to local communities. However, a series of man-made obstacles at Rothes, Speyside, 40 miles east of Inverness, were until recently impassable to salmonids. The removal or adaptation of these obstacles was undertaken as part of the Rothes flood alleviation scheme.

The downstream-most obstacle was a weir and bridge apron at Green Street where shallow flow was impassable to salmon (**Figure A3.27**). Even during higher flow events with greater flow depths, the flow velocity and smooth flow was thought to be impassable. Although high densities of salmon and sea trout had been recorded downstream, no fish had been found in the river above this point during electro-fishing surveys in 2004, 2006 or 2008. Habitat surveys estimated that removing obstacles to upstream migration would open up further 3085 m² of good quality habitat to juvenile salmon.

A3.14.2 The works

The obstruction at Green Street could not be completely removed as this would have affected the structural integrity of the burn banks potentially putting properties at risk.

In the first phase, Green Street Bridge, carrying a disused rail line, was deconstructed and services were protected or diverted. Water was over-pumped during this phase of works. The work was affected by a series of spate events in September 2009 with water levels rising about a metre within hours.

The second phase involved lowering the weir apron downstream of the bridge and narrowing the river. The new channel was aligned along the lowest point of the bed to concentrate flow in one place. A fish pass was designed in co-operation with the Spey Fisheries Trust to ensure that the solution was sustainable and fit for purpose. Locally-sourced cobbles and gravels were used to roughen the river bed. A series of resting pools were created downstream of the pass to increase the variety of flow conditions and provide refuge areas for fry and juvenile fish in particular. Geomorphological stability of the wider reach upstream and downstream of the site was also considered.

A3.14.3 Key construction issues

During construction, there was concern about noise and water pollution arising from breaking out the existing structure or constructing the new. The fish pass layout was located to minimise breaking out and construction activities in the watercourse.

There was also concern that flooding during the works could lead to equipment and machinery being damaged and/or washed into the watercourse, potentially resulting in a pollution incident. To mitigate this, water level gauges were installed upstream to provide notification of rising water levels and increase response time. Consideration was given to working from the bank rather than working in the burn (using long reach excavators) and no equipment and machinery was left in or on the side of the burn overnight or when not in use.

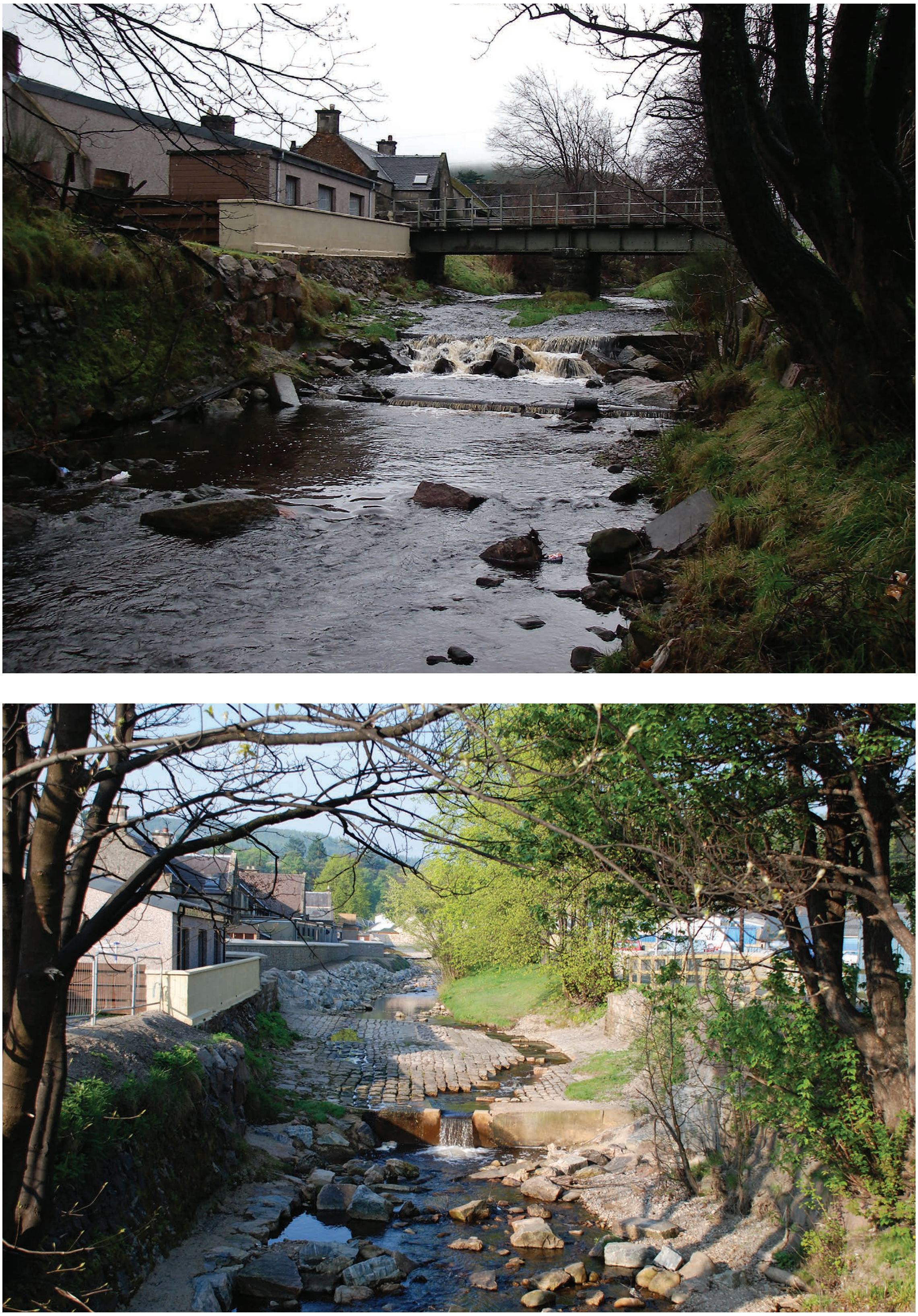


Figure A3.27 Weir before (a) and after (b) improvement

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A3.15 HOO MILL, STAFFORDSHIRE

A3.15.1 Introduction

Hoo Mill is a former mill adjacent to the River Trent, about 5 km east of Stafford, Staffordshire. An access track across the river was strengthened through the installation of a reinforced concrete box section, but the invert of the box section was set above the level of the river bed downstream. Rapid and significant erosion resulted, creating a scour hole several metres deep and causing the invert of the bridge to act as a weir, presenting an obstacle to fish (**Figure A3.28**).

A3.15.2 Rock chute

To overcome the problem, the Environment Agency created a rock chute, sloping at an angle of 1:20, for a length of 30 m downstream of the bridge. Around 700 tonnes of 0.5 m-sized local limestone rock was used to fill the scour hole and create the chute. A trench was excavated across the river at the downstream end of the chute and subsequently filled with rock to provide protection against further erosion. The total project cost was about £15 000, including easement fees of £1400 paid to local landowners for access. Improvements to the boundary of one landowner's property were carried out where scouring had caused the collapse of the river-bank.

Such was the success of the scheme that construction workers observed fish swimming past their feet up the chute as they were placing the final few stones. The bridge invert has a low drop and irregular hydraulic jump and so presents low-hydraulic hazard.

A3.15.3 Remedial works

By 2010, turbulent flow at the transition from the smooth concrete bridge invert to the rock ramp had caused stones to slip downstream. To restore the rock ramp, the first two rows of rock armour immediately downstream of the bridge invert were pinned by driving 10 m long steel H-piles into the river bed on a grid pattern. The exposed pile lengths were below water level and visually unobtrusive.

Although effective for some years, there are signs that the rock ramp is slipping again. With hindsight, replacement of the existing bridge

a Original drop

b Original rock ramp toe slip before refurbishment works, during high water

c After completion of refurbishment works

***Figure A3.28** Hoo Mill access bridge before (a and b) and after (c) improvement (courtesy Chris Grzesiok, Environment Agency)*

with a less intrusive footbridge may have been more cost effective in the long term due to lower maintenance requirements.

A3.15.4 Lessons learned

- Box culverts and bridges with rigid scour protection can behave like weirs by creating a drop in water level.
- Avoid setting culvert invert levels too high (see Balkham *et al*, 2010).
- If possible, consider the removal or replacement of structures that act like weirs.
- A relatively cheap scheme using a rock chute overcame the scour problem and avoided the need for a specially-designed fish pass.
- Monitoring of rock structures is recommended as it was noticed that some movement of rock took place over several years.
- Local road hauliers were reluctant to transport stones larger than about 0.5 m because of the risk of damage to their lorries.

A3.16 FORMER MILL WEIR, NORTHERN ENGLAND

A3.16.1 Introduction

A former mill weir in the north of England was installed over 100 years ago. In 2001, the weir breached, threatening an adjacent millpond and foul sewer in the river bed. Subsequent repairs were short-lived, and in 2002 the weir breached again, requiring a second repair.

A3.16.2 Site layout

The weir spanned the full width of the river with a crest length of about 15 m and raised upstream water levels some 2.5 m higher than they would have been naturally. The weir was constructed of masonry and concrete.

A 375 mm diameter foul sewer installed within the river bed upstream and downstream of the weir passed through the upper part of the weir structure, possibly weakening it, and then, immediately downstream of the weir, continued beneath the river bed.

Water was abstracted upstream of the weir through an inlet structure to an adjacent millpond separated from the river by a four metre high earth embankment constructed on the river-bank. The millpond contained a supply pipe to the adjacent works, and an overflow arrangement allowed excess inflow to discharge back to the river downstream of the weir. There was also a sluice structure midway along the length of the river embankment. The millpond capacity of 11 000 m^3 was below the threshold for the Reservoirs Act 1975 at the time. It was thought to have been polluted with a number of chemicals from the foundry processes carried out at the adjacent works.

A3.16.3 Phase 1 repairs

In 2001, the weir breached during a flood, resulting in the loss of about two-thirds of the crest length. Only one-third of the masonry weir containing the sewer pipework remained, and this was undermined over part of its length. Over the remaining length, effective crest level was reduced significantly to the concrete core of the weir. As a result, water levels dropped by up to two metres upstream of the weir, causing severe erosion of the river bed and banks. This exposed the sewer which had previously been covered by bed material and which had no concrete surround.

In addition, bank erosion affected the toe of the earth embankment to the millpond over a 30 metre length upstream of the weir, and a five metre high masonry retaining wall on the left bank. This caused the collapse of a sluice gate and surrounding brickwork structure connecting to the millpond. Scour immediately downstream of the weir created a sizeable scour hole. Flows were concentrated on the right-hand side of the river following the breach, so there was continuous erosion of the right bank.

The primary concerns were risk of failure of the mill pond embankment and the foul sewer, the collapse of which could lead to pollution. Immediately after the breach, the millpond owner engaged a panel engineer under the Reservoirs Act 1975 to inspect the embankment and provide advice on the measures necessary to maintain its stability. The Environment Agency and local water company (owners of the foul sewer) were also consulted.

Weir ownership was unclear and the owners of the millpond engaged their solicitors to establish ownership. After several weeks of searching, this was found be an elderly person who had been left in ownership following land transfers and property disposals many years ago and no longer owned land or property in the area. He played no part in the work carried out following its collapse.

Repair works comprised construction of the breached portion of the weir as a rock weir with the aim of providing acceptable conditions for migratory fish. The remaining weir structure was improved at the sewer pipe and the pipe was protected by laying concrete filled bags where it was undermined and exposed. The millpond embankment was stabilised by placing heavy stone rip-rap along its toe, with gabion baskets in the immediate vicinity of the weir. Rip-rap was also placed against the toe of the masonry retaining wall on the left bank of the river.

Contamination testing indicated that the millpond water was not contaminated, but that bed deposits contained chemicals from industrial processes carried out historically at the adjacent works. The risk of pollution of the river from these deposits was considered to be low.

A3.16.4 Phase 2 repairs

Two months after completion, parts of the repaired section of the weir crest began to move until, during flood events in 2002, it was completely washed away. A number of the large boulders from the repair were washed into the downstream pool and the remaining weir structure was undermined. The gabions installed to protect the embankment and the rip-rap on the opposite bank provided sufficient protection to avoid any further erosion, but the sewer pipe was once again exposed, albeit supported by bagwork.

Following an evaluation, it was decided to replace the weir with another rock weir, but using larger boulders. A riffle was created upstream of the weir to cover the pipeline that was previously exposed and to form a pool upstream of this. Downstream of the crest of the weir the drop was split into a few small steps encouraging plunging flow and energy dissipation. Further remedial action was taken to place rip-rap along the river-banks to prevent erosion. Following the works, the weir operated effectively with good energy dissipation downstream and there was no evidence of bank erosion or movement of the stone boulders.

A3.16.5 Lessons learned

- Old weirs often no longer serve the function for which they were originally constructed. As such they may be neglected and infrequently inspected (if at all).
- Neglected weirs may be located in places where access is difficult, and may be hidden from view by dense tree and bush growth.
- It is sometimes difficult to trace the owners of neglected structures.
- In cases of failure, prompt action may be needed to avoid a flood or pollution incident, and to restrict the amount of damage caused to adjacent structures.
- The stability of rock weirs requires careful consideration. In particular the size of stones used, the thickness of the rock layer, the need for an underlayer of gravel or geotextile to prevent fine foundation material from being washed out, undermining the rock, and the need to stop flow passing through the rock structure (in low flows this would cause the weir to appear dry, in high flows it could destabilise the weir).
- In this case, it might have been more appropriate to replace the weir with a concrete structure, faced with masonry to mimic the original structure. However, this will depend on the setting of the structure and its heritage value.
- Demolition of a weir that has collapsed may be the best option, but the impacts of so doing (engineering and environmental, short-term and long-term) need careful investigation before the decision is taken.

A3.17 LITTLE BOLLINGTON, CHESHIRE

A3.17.1 Introduction

Little Bollington weir is a mill weir on the River Bollin within the National Trust's Dunham Massey Hall estate, Altrincham, Cheshire. A flow measurement station was required to monitor low flows for water resource purposes. Alternative locations and solutions such as electromagnetic gauges were considered, but were discounted for a number of reasons. It was eventually decided to undertake remedial works to the existing weir at Little Bollington. The weir structure would remain under the ownership of the landowners.

The works would provide a flat-V weir for gauging purposes without causing significant effects on this sensitive area or altering the existing river regime (**Figure A3.29**). Significant temporary works were required to enable construction, but these were designed to provide residual environmental improvements once construction was completed.

A3.17.2 Temporary works

Flows in the river range from a minimum of about 2 m^3/s to an in-channel capacity of about 37 m^3/s. The higher flows could not be contained within a temporary flume through the work, and there was insufficient space for a bypass channel. The only option was to make use of a badly silted and debris-strewn millrace running from upstream of the weir, under a residential mill complex, and discharging some 100 m or so downstream of the works. The millrace and structures adjacent to the channel required considerable protection works to cope with the expected high flows and velocities (**Figure A3.30**).

The design of the temporary works was dependent on the flow capacity of the millrace and the requirement not to increase the frequency of or raise flood water levels upstream of the works. This resulted in a restriction in the height of the

Figure A3.29 Weir before (a) and after (b) improvement

Figure A3.30 **River flows before (a) and during (b) the works**

sheet piled cofferdam that was designed to overtop before the millrace capacity was exceeded. The works were suspended for some months over the winter period while flows were prohibitively high, making activities on the weir face such as piling and laying the stone sets impractical.

A3.17.3 Permanent works

The works involved removing the top section of the existing weir and reconstructing it to comply with British Standards. The new top section was founded using 36 eight metre long concrete piles into the underlying mudstone. Both the wingwalls and the weir structure were constructed from reinforced concrete and clad using stone setts.

A3.17.4 Public and landowner relations

Before the diversion of the river flows, protection works to the millrace, which ran on the eastern side of the weir, had to be undertaken. Access to the eastern bank was via a private road upon which were located two small bridges. Structural surveys of the bridges, one of which was a listed structure, confirmed their unsuitability to carry heavy traffic. Discussions with the landowners resulted in the leasing of adjacent fields and the construction of a bypass route including a temporary bridge.

The Dunham Massey Hall estate is open to the public. To assist with the works a permissive footpath was diverted. However, the working area was still visible to the public and prompted a keen interest from visitors to the hall. Information boards were positioned at strategic locations and a briefing sheet was prepared for the contractor to respond to enquiries. Due to the location of residential properties, the timing of noisy construction operations, particularly the piling works, was restricted. Monitoring was undertaken to ensure compliance with the acceptable noise levels specified by the LA.

Adjacent to the weir is a mill building that has been converted into residential apartments. The millrace runs underneath it where a water wheel would have been located. The residents took a keen interest from the initial proposal stage, and sought to influence the design. A number of residents' meetings were held during the design and construction process at which the programme and progress were discussed. These prompted several debates during which the rationale behind the project was explained.

New weir crest neatly joining the existing glacis

Stone facing to the concrete walls

Completed wall and instrumentation building

Figure A3.31 Permanent works

Resistance to the works, due principally to the disturbance involved, was significantly overcome by encouraging the residents to participate in the development of the environmental improvement works (an area they were particularly interested in) particularly to the millrace.

The National Trust, as the owner of the weir, also took a keen interest in the development of the design and throughout the construction of the works. The aesthetic appearance of the completed structure was paramount in obtaining their agreement and, following lengthy negotiations, the weir and gauging hut were constructed from materials that complemented the other structures on the estate (**Figure A3.31**).

Given the rich historical heritage of the area, an archaeological watching brief was commissioned under the guidance of the assistant county archaeologist. A report on the archaeology was archived at the local studies library. Excellent relationships between all parties meant that there were no delays due to recording information or the archaeological investigations.

The River Bollin is used for canoeing. The weir provides a canoe-friendly slide at low flows, but has potential to become hazardous at high flows.

A3.17.5 Lessons learned

- Old mill weirs can be converted into flow monitoring structures.
- Works on old weirs often present opportunities for environmental enhancement.
- Early consultation with all stakeholders helps to ensure a successful project. In particular, engaging members of the public and local residents in the design and construction process can considerably improve public relations.
- Involving the LA archaeologist early in the planning stage will help to avoid delay and disruption of the construction process.
- Temporary works are often an important consideration, especially when dealing with flood flows.

A3.18 NORTHENDEN WEIR, MANCHESTER

A3.18.1 Introduction

Northenden Weir is a former mill weir situated on the River Mersey, Northenden near Stockport, thought to date back to 1530. Rehabilitation was required as the weir-obstructed fish passage had suffered damage to the apron. Although no longer needed for its original function, the weir is important in maintaining the regime of the river at this location.

A3.18.2 Survey

The drawings produced following a survey of the weir are given in **Figures A3.32 and A3.33**. The weir spans the river diagonally, with a 50 m long crest that is gently curved on the plan. It is located on a right-hand bend in the river, and the crest level is slightly higher on the outside of the bend. The downstream apron of the weir is gently sloping over a length of about 15 m and comprises six bays.

The weir crest is formed from sandstone blocks, 1.2 m to 1.7 m long and 0.5 m wide. The crest blocks sit on a masonry wall, whereas the masonry apron sits on a grid of timber piles backfilled with gravel and clay. The weir was believed to be designed as a 'wet weir', ie somewhat permeable so that the timber piles remained moist.

A3.18.3 Rehabilitation

Rehabilitation works were undertaken to repair two bays adjacent to the right bank and install a Larinier-type fish pass. The repairs comprised replacement of the existing damaged sandstone blocks with a reinforced concrete apron. The concrete apron was pigmented and finished to mimic the existing masonry (**Figure A3.34**) and the joint between the new concrete and existing masonry filled using an epoxy mortar. The concrete apron was underlain by a granular layer with outlet pipes to maintain free drainage.

The works were carried out inside a temporary cofferdam formed from a clay core protected by rock, with sandbags providing additional height.

Northenden Weir forms part of the River Mersey canoe trail. The mild sloping apron forms a long slide for paddlers and hydraulic conditions are safe for canoeists over a wide range of flows (**Figure A3.35**), although the weir is reported to be dangerous in high-flow conditions. Steps have been provided on one bank to allow inspection and/or portage around the weir.

A3.18.4 Lessons learnt

- Detailed surveys are important to determine the nature and extent of remedial works required.
- The foundations of old weirs often include timber piles.
- While simple cofferdam arrangements (eg earth bunds) may be all that is needed for remedial works to existing weirs, it is important to consider the impact of flood flows on these, both in terms of crest level, and also resistance to erosion.
- For weirs on permeable foundations, it is important to consider under-drainage.

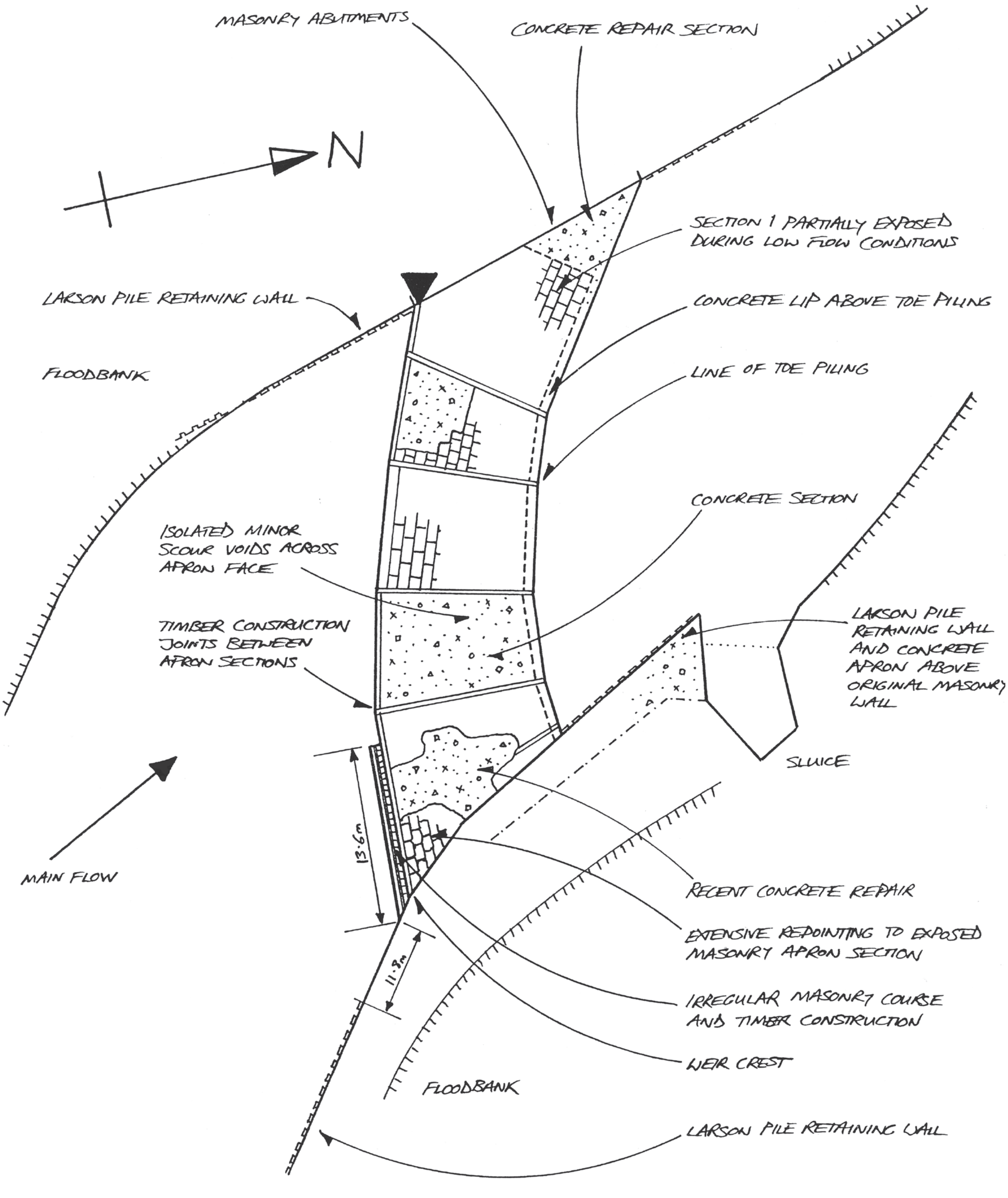

Figure A3.32 Plan of Northenden weir

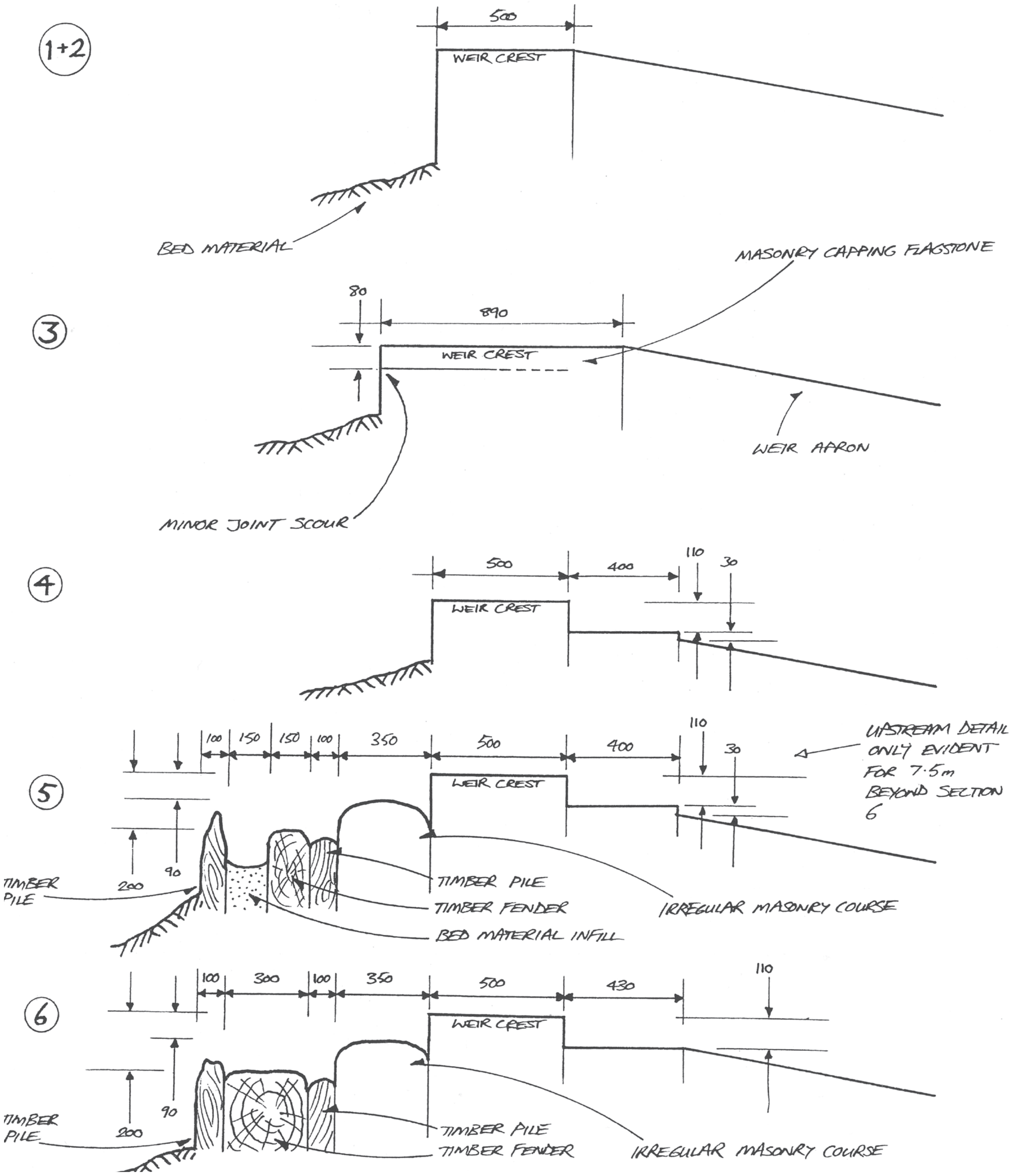

Figure A3.33 **Cross-sections through the weir**

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Part of the weir isolated by a temporary cofferdam

Timber piled substructure revealed by excavation

New weir taking shape adjacent to the fish pass

Figure A3.34 Work in progress

Figure A3.35 Northenden Weir today

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June 2016

A weir is an impounding structure in a watercourse over which water may flow and which increases water surface levels upstream over a range of flows. Weirs have been in use in the UK for hundreds of years, to manage water levels for navigation, land drainage or flood risk management, provide a unique stage-discharge relationship for flow measurement, stabilise channels, enhance the landscape or provide recreation, or for commercial reasons such as abstraction, hydropower or fish counting. Fishing weirs have been used since Neolithic times.

This good practice guide replaces guidance published in 2003. Since then, comprehensive lessons have been learned in terms of operational safety and, following the implementation of the Water Framework Directive (WFD) 2000, it has led to a greater focus on weir removal.

Although the majority of work on weirs is still carried out to maintain the current functions of weirs, this guide focuses on the alteration of weirs to benefit ecology, reflecting an industry need for more information on topics such as geomorphology, environmental issues, alternatives to weirs and weir removal. This guide encourages the reader to ask whether a weir is the best option and to consider weir removal as a preferable design option, should assessments show this to be feasible.

Canal & River Trust

Department of Agriculture and Rural Development
www.dardni.gov.uk

Department for Environment Food & Rural Affairs

Environment Agency

Cyfoeth Naturiol Cymru
Natural Resources Wales

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